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DISPLAY INSTRUMENTATION FOR V/STOL AIRCRAFT IN LANDING

by

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DISPLAY INSTRUMENTATION FOR V/STOL AIRCRAFT IN LANDING

volume 1

Experimental Investigation and Results

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by

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ABSTRACT

This thesis concentrates on the instrumentation of aircraft, facing the problem of steep angle approaches or landing in zero-zero visibility.

A V/STOL aircraft (of the tilt-engine type) has been simulated, using the non-linearized form of the equations of motion, and has been flown from cruise altitude to touchdown with severe wind disturbances, descending along glideslopes of 4.47°, 8.87° and 17.3°.

Three kinds of instrumentation have been used : a conventional set of cockpit-like instruments, the same set augmented by means of a flight-path profile display, and a contact analog perspective glideslope indicating system.

A general display program has been written, to display a skeleton scenery, consisting of lines connecting characteristic points. The lines in this application are the runway boundaries, the glideslope lines and several distance indicating poles. The display is generated on a large screen cathode ray tube, using an analog line drawing scheme. The picture changes dynamically and is updated by a digital machine sixteen times per second, using the translational and rotational rates of change, resulting from the motion of the observer.

The piloting task consisted of staying in level flight until intercept of the glideslope, then in tracking the glideslope to hover and in landing the aircraft with minimum impact velocity and maximum accuracy. The task was quite difficult, because of the lack of stability augmentation.

Three classes of pilots of different experience have been examined and different control techniques have been observed with the regular set of instruments. They all performed equally well with the perspective glideslope indicating system.

The value of the perspective glideslope indicating system has been shown in :

1) the ease of performing coordinated maneuvers, allowing large but quite precise changes of the flight variables,
2) the consistency of touchdowns,
3) accuracy of tracking the glideslope, with dead beat response,
4) the learning curve, and
5) the effectiveness of the representation of the integrated real world outside picture.

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TO MY WIFE MONIQUE

who gave meaning and help
in this immeasurable struggle
and whose encouragement and understanding
helped me go through the impossible.

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P R E F A C E

L.S.*

In 'thesiologie'**, it is generally accepted that the quality of a thesis is the inverse of the quantity or volume. Indeed,... but the exeeptions make the rule.

The author's opinion is that it should be possible for a very interested and highly motivated person, with some familiarity of the material discussed in the thesis, to understand, to use and to repeat the work or the experiment described therein in a reasonable period of time.

This means that the work should be fully documented with relevant material, which is the product of a personal effort, but not to the point of saturation nor repetition. Results should be in no way exaggerated,nor should numerous tables or plots be given, and the reader left to draw his own conclusions.

This has been the underlying idea in preparing this thesis. The material has been divided in three self-contained volumes for easier handling of the material. Volume 1 is written for the person interested in contact analog and electronic displays, as well as in their evaluation in landing applications. Volume 2 is written for the person interested in computer graphics, hybrid simulation and on-line data taking. Volume 3 is written for the person interested in real-time simulation, on-line data-processing, and computer programming in general.

* L.S. (Latin : Lectori Salutem) : Hail to the reader
** Thesiologie (Greek : θέσις,thesis ; λόγος, study)

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CHAPTER 1

INTRODUCTION

Science and Technology know no rest. What was a dream a decade ago is reality today. Yet in this rapidly changing world of technology,problems seem to build up as quickly as solutions have been found for others. The evolution has come to the point that it is no longer acceptable to solve the present problems; one has to cope with the problems of the future.

A simple look around us makes us well aware of the size and the importance of some of these technological problems that need a solution as soon as possible. One such area is air travel. The present traffic volume has grown so fast that airports are now vital links in the trade, the economic life, and the business and tourism of every nation. The solution to the problem is not simple, especially considering the increase in volume in the near future given the present level of air traffic congestion, the arrival of the jumbo airliner, STOL aircraft and the SST, and the requirement for all weather operations. Important factors that play a role are: safety, economy, and continuity of the air travel service for the passenger, noise elimination for the people on the ground. Serious efforts in each discipline combined with efficient interaction between disciplines could result in significant improvement.

1.a. General Area of Study

The work in the area of display instrumentation can concentrate on many points of interest. In particular, it can look more deeply into (1) the problems the pilots are faced with, such as: psychology, optical illusions, vertigo, information transfer rate, information processing capability, or workload; (2) the problems related to the aircraft: conventional, V/STOL or helicopter; (3) problems related to the mission: landing or take-off under various angles of the flight path; or (4) general problems of navigation and air traffic control. Each of these elements is reflected in the cockpit instrumentation in some way. Furthermore, work in this area may result in just another display among so many already in existence; or the work may concentrate and evaluate different systems. The product of the studies could also be a method for evaluating display instrumentation.

The present effort has been aimed at looking into specific kinds of instrumentation for STOL aircraft and criteria for evaluating them. An elaborate literature is available on work done in this area.

1.b. Background

Air traffic has grown by four times during the past ten years (90), and there is sufficient evidence that domestic and international traffic will continue to expand at a rate which will further double the volume every five or six years (90). The present situation has already become such that efficiency and economy are decreasing. In the Northeast corridor the largest volume of traffic in history was observed in 1969, and Eastern Airlines identified close to $1 million of non-productive flying costs. During the same season, delay times at Kennedy Airport reached an average of three hours, while airplanes got in the "waiting line" for take-off. This problem of congestion is an indication of the present limitations of the aircraft, the air traffic control system as well as of the pilot and instrumentation. Challenges are many.

The VTOL Aircraft has been looked at as a possible solution for the congestion problem (20), (93) and non-passenger trial STOL operations have been conducted by Eastern Airlines (6). Also, air taxi operators have been successfully operating essentially STOL equipment for a number of years. Research has begun in the technical area (33), (115), (123) and studies on economic feasibility for VTOL transportation are underway (112), (128). There is no doubt that the workload of the pilot has gone up significantly as modern aircraft have come into service (8), (67), (77) and that the instruments that are available to the pilot are hardly suitable for the task (164). Improvements of some of the instruments (5), (66) may help somewhat, but they do not take away the burden of the pilot's task.

Continuous research is going on in two directions: one is the fully automatic landing, the second one is the electronic display which still leaves the pilot in the control loop. The first studies and the implementation of the automatic landing system resulted in a demonstration on December 8, 1964 (170), of the All Weather Landing System of Lear Siegler Inc. At about the same time, Sperry Gyroscope Inc. was studying and testing on electronic display (73), (163) to use as a guidance means for all weather operations (58), (59). Although the automatic landing is far more attractive, by far more research has been done on improved electronic display systems (85), (146), (155). Not only for conventional and for V/STOL aircraft, but also for the SST, the electronic display is the approach taken today (76) and many aspects of this area are being examined (27), (29).

New display concepts and new ideas are set forth and are being tested in an attempt to solve the present day problems (61), (62), (63). The general approach is to use the computer to do the "thinking" work and to present the pilot with a picture whatever is necessary to meet requirements on accuracy (143) and feasibility (120) and simulations are set up to study the potentials of control representation on the contact analog (139), (148).

A good and complete survey of electronic and optical displays for aircraft (80) is available. It presents not only the displays currently being investigated, but also gives requirements and standardization of these displays. Simulations have been done to verify these considerations (92), (82), (72) as well as studies on the handling qualities of these difficult to maneuver aircraft (2), (19), (21), (109).

The general consensus is that an improved instrumentation is necessary in order for the pilot to adequately control the aircraft (87), (96), (126) and ground based simulation (94), (102), (114), (129) as well as real flight investigations (47) are available. Several display concepts for landing have been examined. They can be classified as: contact analog display (37), (45), (46), the Heads-up display (103), (134), the optical landing system (107), the pictorial navigation system (109), (130), and the vertical situation display (18), (165). Several examples are shown in Fig. 36.

Besides the problem of congestion, there is the equally pressing problem of all weather landing, which is the major aeronautical challenge of the 1970s (84). Although the minimums for aircraft landing have steadily gone down, and the technology seems to be promising for better, the British do not plan operational landings of even 700-ft. visibility for some years (84).

1.c. Objectives of the Thesis

This thesis concentrates on the "display/pilot" interface to evaluate a perspective contact-analog display. It has been examined and compared with a conventional instrument panel to evaluate:

1. The information available in the cockpit
2. The information processing by the pilot
3. The decision and response from the pilot
4. The flight response of the vehicle

The system under investigation can be represented by Figure 1. The pilot's task is indicated in Figure 2.

This pilot control loop has been looked at from the following viewpoints:

1. Systems response
2. Pilot performance which includes learning and fatigue
3. Overall efficiency of display-pilot-vehicle

A restriction on the general research area has been introduced by concentrating on the landing phase. It is the most difficult task of the flight and is the limit on the present air traffic (154). Of special interest is the study of the longitudinal motion, (planar case), since the lateral control is far easier than longitudinal control for manual as well as for automatic control (50), in steep but not vertical approaches.

This investigation examines:

1. the information available in the perspective display

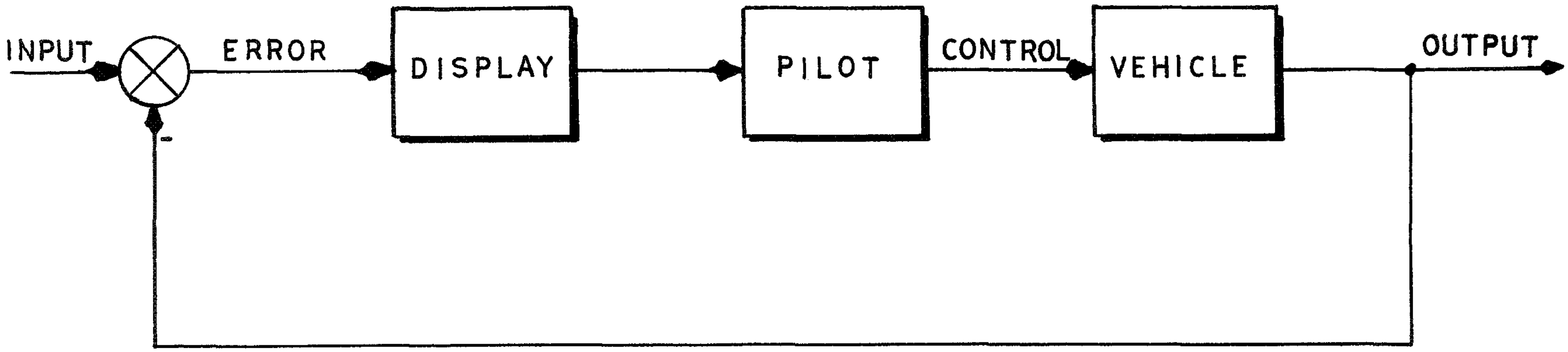


Fig. 1a Functional representation of the control system.

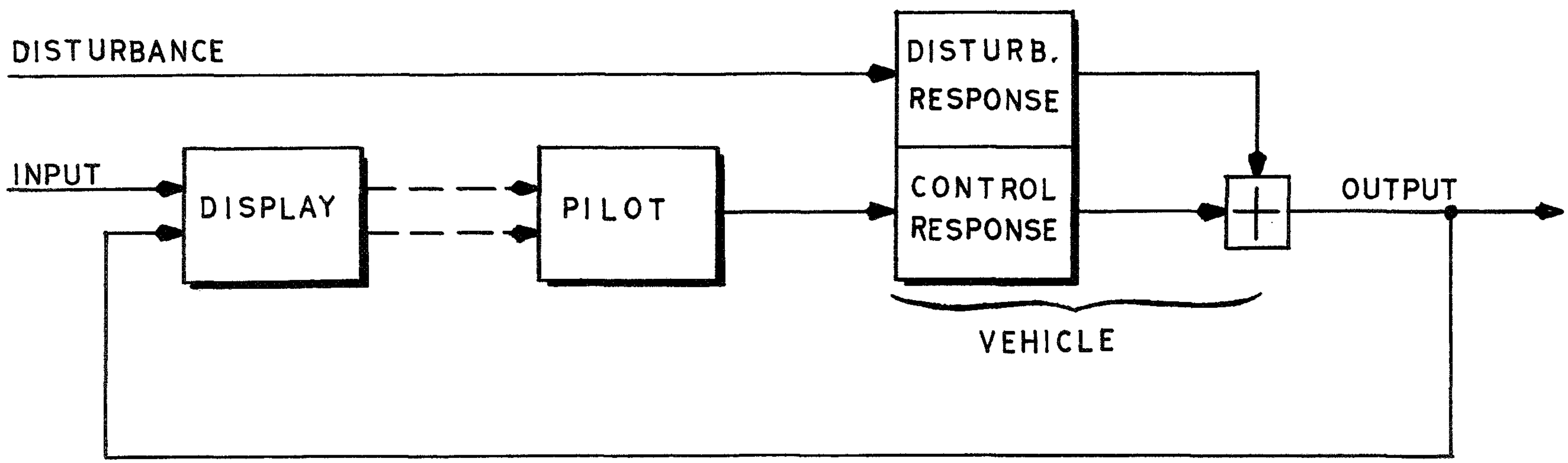


Fig. 1b. Functional representation of the control system with a disturbance.(Ref.1)

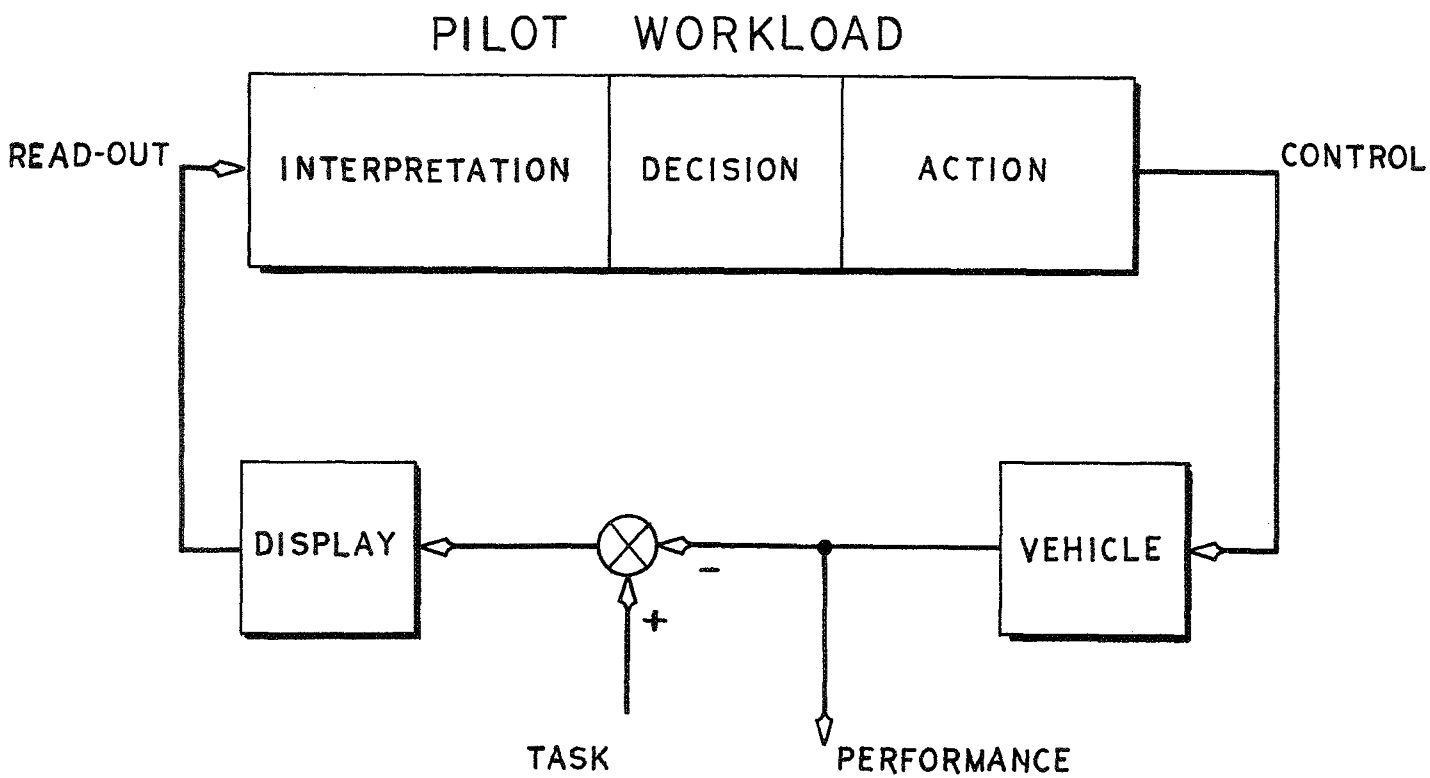


Fig. 2. Functional representation of the pilot's task.

as well as the information given by different elements (e.g. intensity, gain, size) or other components (e.g. velocity vector)

2. the pilot performance from the point of view of accuracy (e.g. tracking illusions) and learning (i.e. familiarization with the task)

3. the piloting technique for controlling the aircraft in different phases

It is believed that the tendency in the display design has been to "improve" the picture by adding more and more "available" information with the result of a cluttered presentation. For that reason, the display and the pilot have been looked at as a whole to improve the overall systems response.

1.d. Justification of the Work

Experiments have been performed to give answers to the following questions of basic interest:

1. What should be displayed to the pilot to achieve a given level of performance in the task of landing a VTOL?

2. How big a step can be made using a display of this type, in the direction of a safe zero-zero visibility landing? The ICAO* standards are given in Table 1.

*ICAO : International Civil Aviation Organization

3. What are the kinds of glideslopes that the "pilot-vehicle" will be able to handle with the V/STOL aircraft?

4. How much can approach procedures be modified, using the better displays?

5. What may be the impact of improved displays on related problems such as aircraft noise, etc?

Each of these points will be described briefly to indicate its importance in the examination and to better understand the methods used to quantify these parameters.

TABLE 1: ICAO Low-visibility Landing ILS Categories (Ref. 84)

Category	Runway visual Range (RVR) ft	Decision Height (DH) ft
I	2400	200
IIA	1600	150
IIB	1200	100
IIIA	700	-
IIIB	150	-
IIIC	0	-

1. Information Available in Cockpit

To be able to adequately control the aircraft, the pilot needs the following information:

a. attitude: roll, pitch, heading
b. speed: airspeed, vertical speed, ground speed
c. guidance: glideslope deviation, course deviation range, height

He scans his instruments, one at a time, to get the necessary information on the position and attitude of the aircraft. He will learn to develop a scan pattern, and to distinguish the prime instruments from the secondary instruments which may be dependent on the mission or the phase in this mission. He learns to give the leading instruments priority to eliminate control of his own remnant, e.g. he will watch the artificial horizon carefully to derive the rate of sink, and he uses this variable to control the altitude of the aircraft.

2. Information Processing

Using the information the pilot gets from the instruments he derives the motion of the aircraft. In most cases, this "picture" of what is going on is derived moment by moment and the task is more or less easy since "integration of the picture" is not too hard. He tends to ignore extraneous or misleading information such as the motion cues in a big airliner. He rather relys upon the truthful visual information. At times though, he may get disoriented in which case the integrated picture "gets lost" and he needs to "reinitialize" the picture of what is happening. This he does by interpreting each instrument separately and then combines this information to "get the picture" again. One can readily see what the hazards are in this type of information processing and reinitialization.

- misreading dials for various reasons,
- oscillating needles preventing reasonable readout,
- unawareness of the conditions of some variables (high sink rate, or distance to go),
- no indication of the variables or meters which triggered an emergency situation,
- difficulty in establishing the effect of a control change.

The whole process, furthermore, involves quite a bit of skill, an intensive training, and can be very fatiguing for the pilot in the modern aircraft.

3. Decision and Action

Based on the picture of motion of the aircraft and taking into account the desired path, he will make decisions to take action and he will set the controls accordingly. Again this action takes training and familiarization to use the proper control settings for each particular aircraft. There is not a unique correspondence between instruments and controls, but rather a varying cross-coupling between controls and instruments. Moreover, the information the pilot derives from the instruments is a status information for each of the variables involved. He will try to guess the new situations using what he may get from moving indicators and, in a way, he will try to anticipate the situation, where sizable changes in the control could bring along drastic changes in attitude and position. Finally there are the operator delays involved in the information processing as well as the lags in the instruments and the system as a whole.

4. Flight Response of the Vehicle

The ultimate goal when flying an aircraft is to a accomplish the mission as well as possible: e.g. an optimum path (minimum fuel, minimum noise, maximum safety); an accurate descent (minimum deviation for maximum air traffic density); or a smooth landing (minimum touch down speed, maximum accuracy on touchdown). The conditions, however, can be very much different, e.g. the type of aircraft, etc., (V/STOL, helicopter), the glidepath (3° or 9° or even 15°), the landing spot (runway, carrier, building), or the weather (cross-wind, fog, zero-visibility). The task itself may change, depending on the flight mode, e.g. cruise, transition or hover.

From what has been described above, it is obvious that the system "display-pilot" is a complex unit in the control loop of the aircraft. It is not possible to describe it in terms of modern control how it acts under all circumstances, nor does it lend itself in an easy fashion to a complete study. Many studies have been concentrating on single aspects of parts of the system and some positive conclusions have been shown giving the pros and cons of the changes in the system that was investigated. The conventional method of displaying the information to the pilot by means of instruments has been used and has been compared with a configuration in which it was thought he had only to be the decision maker. In his action the pilot is still able to control in an adaptive fashion, or in a manner which can deviate severely from the norm. Yet, the maneuver can be done safely without taking any chances.

It is often argued that the only way the aircraft control problem can be solved is by implementing an automatic control system. However, there are still many technical obstacles to overcome, (131) and even in the event that the automatic system is used, there is still the problem of defining a backup in the case of failure. For more advanced aircraft and less trained or less experienced pilots, it will be necessary to have even better displays in case the pilot needs to take over. This suggests continuing research in this direction.

1.e. Results of Thesis Research

The experiment has examined a perspective display in connection with a VTOL-aircraft of the tilt-engine type, and the display has been evaluated. The simulated aircraft has been flown from cruise altitude to touchdown with severe wind disturbances, descending along glideslopes of 4.5°, 8.8° and 17.3°. Distinct control techniques have been observed among three classes of pilots of different experience. The value of the perspective glideslope display has been shown:

1) in the ease of performing coordinated maneuvers allowing large but quite precise changes of the flight variables.
2) in the consistency of the touchdowns: the standard deviation is much smaller, with the display than is the case with the conventional instruments.
3) in the accuracy of tracking the glideslope with dead beat response.
4) in the learning curve: the learning time has almost been eliminated.
5) in the effectiveness of the representation of the integrated real world outside picture.

The same display format with slight modifications can be extremely useful for quite a few applications including cruise and take-off.

CHAPTER 2

EXPERIMENTAL SETUP - PROCEDURES

2.a. Experimental Design

In order to best achieve the objectives set down for this study, careful attention has been given to the preparation and design of the experiment. To obtain as much information as possible, the experiment has been organized in a development phase, where preliminary results have been used to set up a well-defined experiment plan, and in the actual experiment phase. (The latter included a training phase where pilots could work up to steady state performance.) The task was to land the simulated VTOL aircraft, and only the longitudinal control was considered.

1. The types of instrumentation examined for comparison are given in the table.

TABLE 2: Types of Display Instrumentation

I.	Conventional aircraft instruments.
II.	Conventional aircraft instruments augmented with a flight profile view.
III.	Perspective glideslope display.
IV.	Perspective glideslope display, modified to meet pilot's requirements.

The first condition is one in which only the usual set of instruments is available. A picture of the cockpit is shown in Figure 3. The pilot knew the magnitude of the variables with the indication of the scales. They were, however, not provided with the conventional dial format units. This allowed us to look into the problem of learning.

For the second condition, as a standard measure for performance, the regular set of instruments was used in connection with an X-Y plotter display showing the flight path.

The latter instrument was used to provide additional information, such as distance to go, provision for duck-under, etc.

The third condition is the one in which the pilot only has the perspective glideslope display, with one single added instrument: the ground speed indicator. This instrument allowed him to see if he was still going forward, because this is the most difficult cue to pick up. This instrument was to some extent necessary because the simulation aircraft dynamics had been set up so that pitch control reversal occurred while going backward. This shortcoming could not be taken out due to lack of memory space for more elaborate programming in the simulation part. The description of the display is given in a separate chapter.

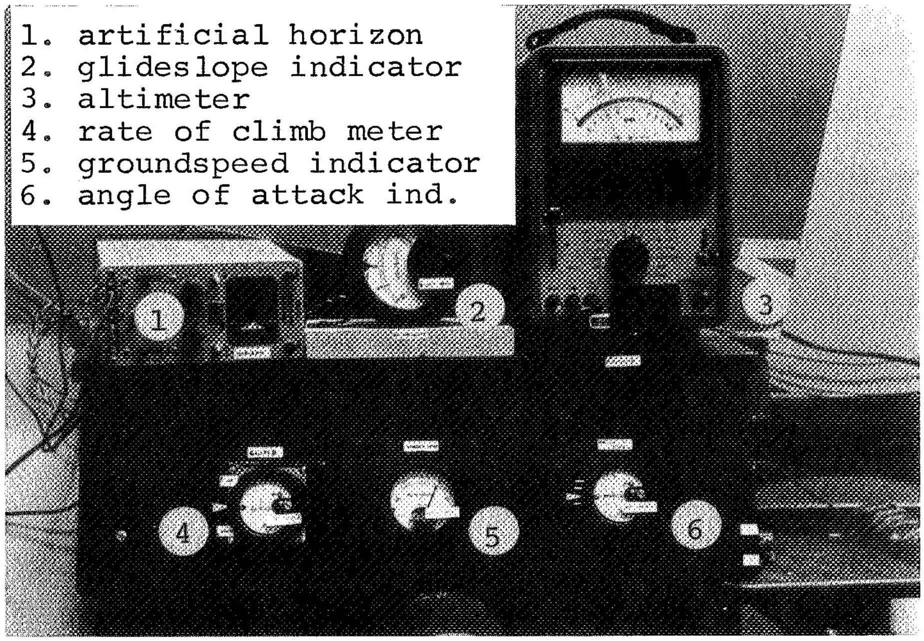


Fig. 3. The Instrument Panel of the Fixed Base Simulator.

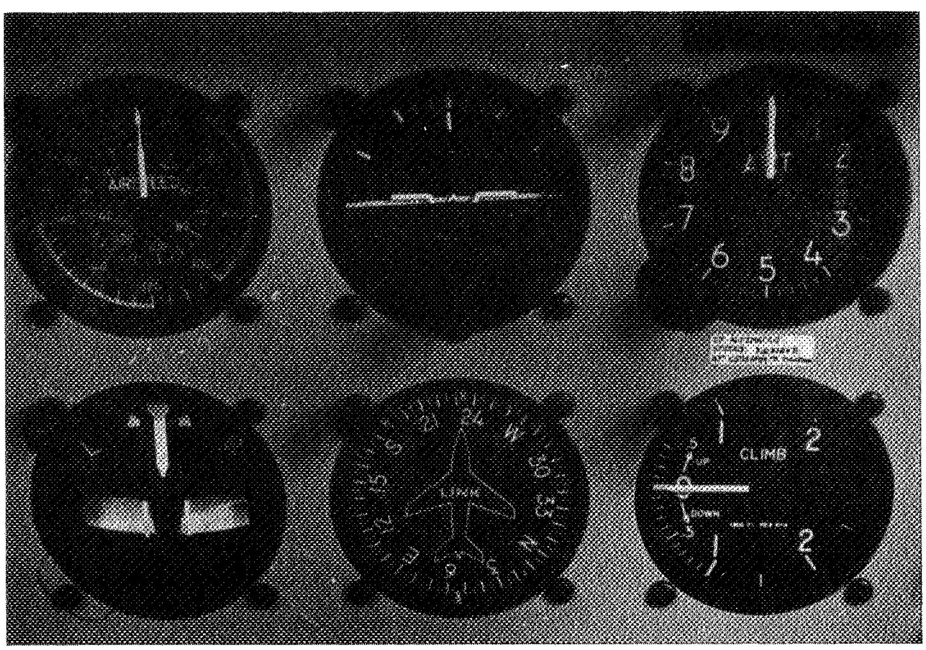


Fig. 4. The Instrument Panel of the GAT simulator trainer.

The fourth condition is one in which the display was altered to get the desired cues which help improve the flight at various stages. The modification and its effects are described with the results. These modifications were suggested by the pilots.

2. To test the population of pilots, three classes of pilots have been examined.

- well trained and highly skilled pilots
- pilots with limited experience
- inexperienced subjects

Their qualifications are given in the section on pilots.

3. The order in which the type of displays have been examined is from I to IV in Table 2. The order in which the pilots have been examined is from inexperienced to highly skilled pilots for each condition. This allowed the possibility of checking minor difficulties in the set-up without seriously affecting the training or performance of any class of pilots.

4. To test the influence of one display condition upon the other, another set of three pilots went through the series of four types of display information in just the opposite order. The effects are given in the discussion of the results.

5. Different glideslope angle conditions were examined to get an idea of the difficulty of control. Among the possible situations, the following were selected: shallow (4.47°), medium (8.87°) and a steep glideslope (17.3°). These numbers correspond to initial altitudes of 6,250 ft., 12,500 ft., and 25,000 ft., respectively for the glide (Fig. 11). These numbers were chosen for convenience in the programming in the early stages.

2.b. Experimental Apparatus

The main point of interest was to examine the presently existing methods of instrumentation and compare this with a contact-analog display. The various kinds of display instrumentation have been examined in a fixed-base simulator.

1. The conventional instruments used are (Fig. 3):
   a. artificial horizon
   b. glideslope indicator
   c. ground speed indicator
   d. vertical speed indicator
   e. angle of attack indicator
   f. altimeter

The arrangement is similar to a flight trainer set up (Fig. 4).

2. The controls available "to fly" the simulator (Fig. 5) with three degrees of freedom (longitudinal plane):

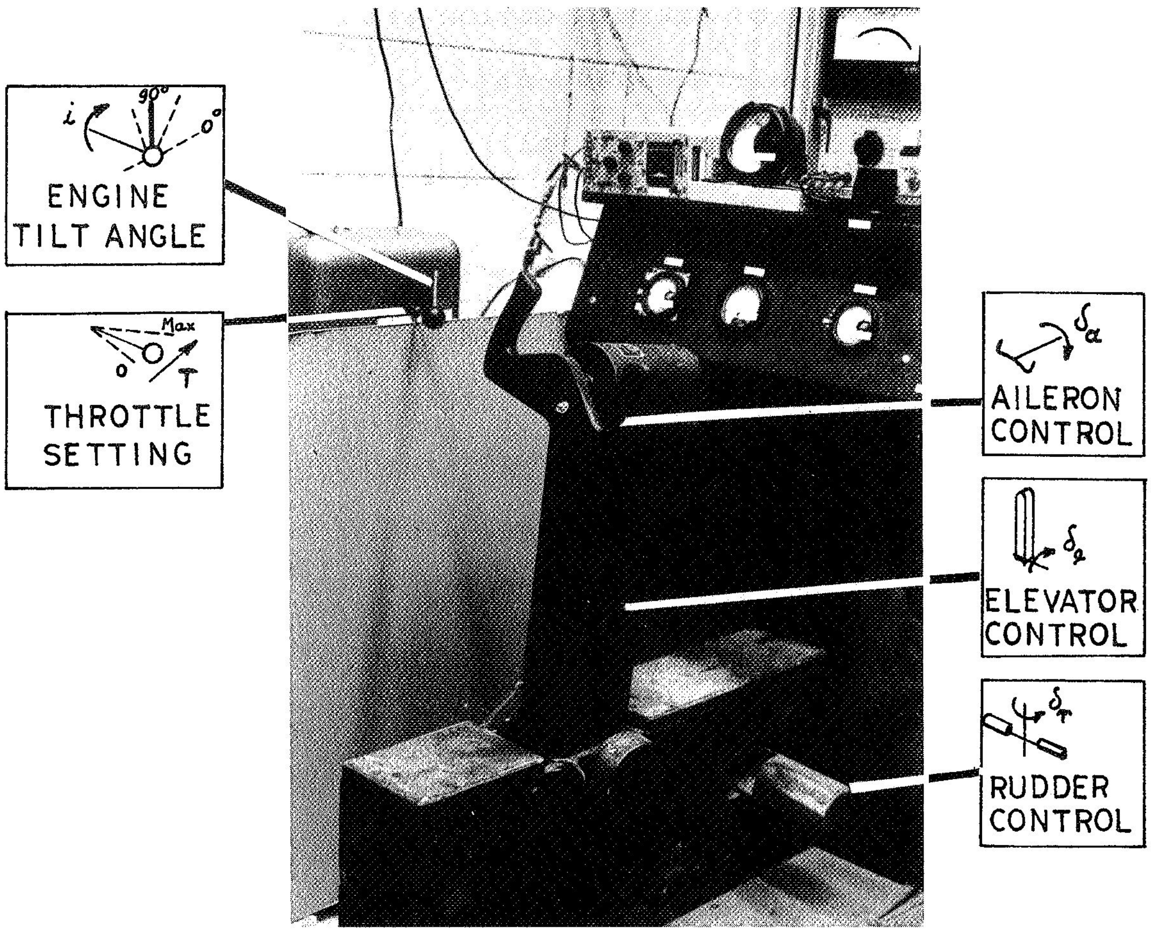


Fig. 5. The Controls in the Fixed Base Simulator.

a. throttle setting

b. engine tilt angle setting

c. elevator control (pitch)

For the six degrees of freedom motion with the display, the following controls were added:

d. aileron control (roll)

e. rudder control (yaw)

3. The contact analog display has been presented on a large screen oscilloscope, mounted in the same simulator. The other instruments were not operating.

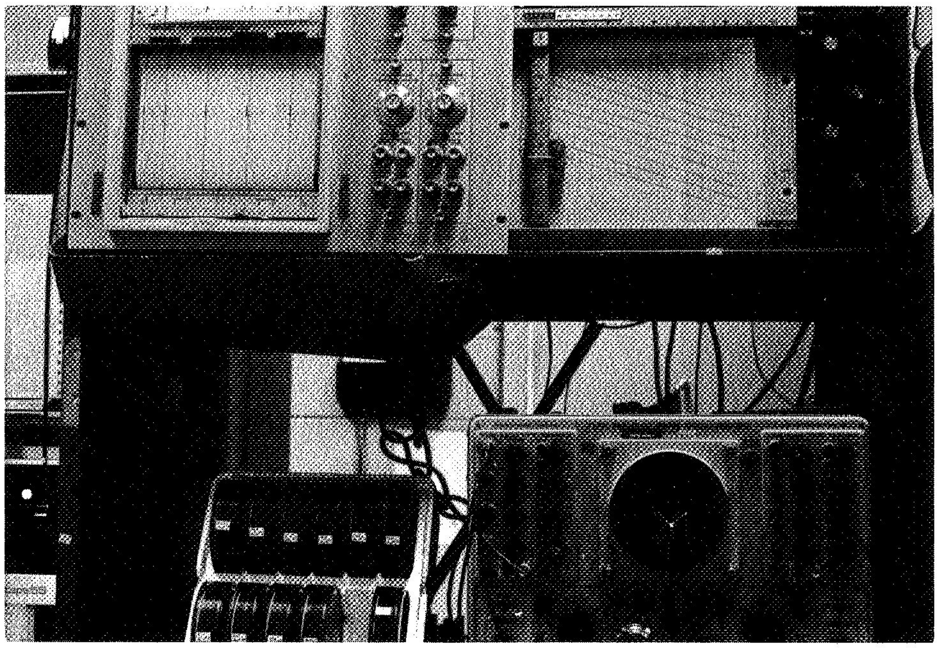
4. The flight profile has been recorded on an X-Y plotter and the same instrument was available in the fixed-base simulator for the condition II of Table 2.

5. Time histories of the flight variables have been recorded on a strip chart recorder. This was a means to establish malfunction of equipment or loss of control of the pilot. Figure 6 shows the chart recording equipment.

6. A signal, representing wind disturbance, was prerecorded on an FM-tape recorder. The signal is a sum of twenty sines and the amplitude spectrum is a simple staircase: 1 volt - 0.1 volt. The peak value of the signal is 4 volts and corresponds to 50 ft./sec. wind velocity. Details on the signal are given in Volume 3.

7. The computing facility is a hybrid system consisting of a PDP-8 (Fig. 7) and a GPS-290T (Fig. 8). The

STRIP CHART RECORDER X-Y PLOTTER



DATA TAPES OSCILLOSCOPE

Fig. 6. The Experimenter's Station, showing the strip chart recorder, the X-Y plotter and the dual beam oscilloscope for monitoring the experiment.

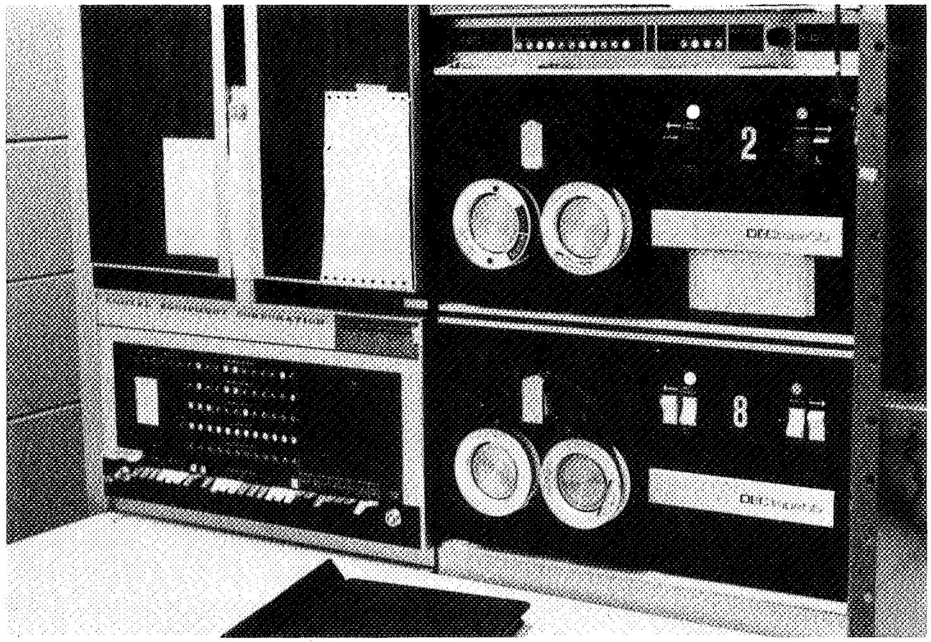


Fig. 7. The PDP-8 : digital portion of the hybrid system.

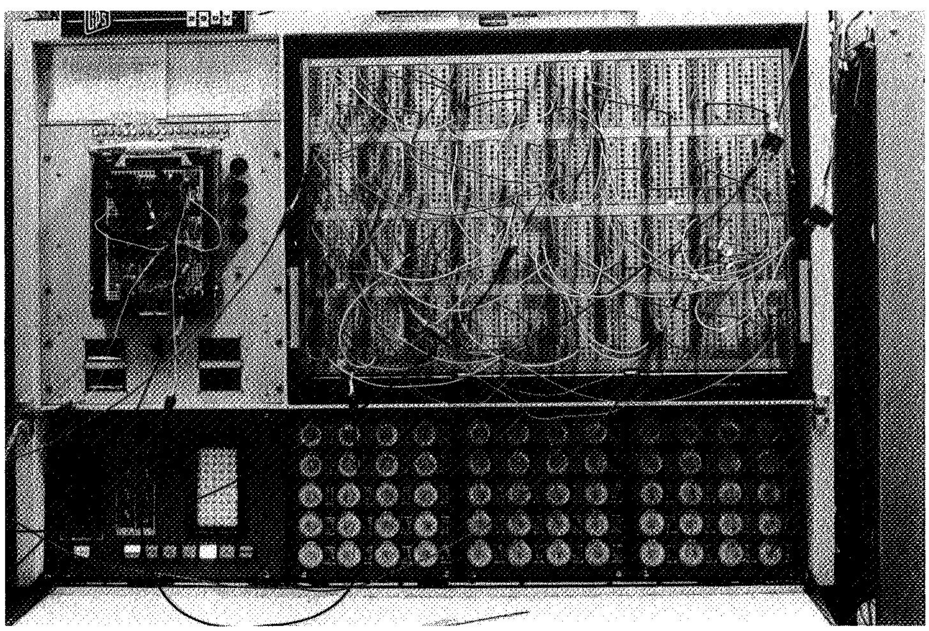


Fig. 8. The GPS-290T : analog portion of the hybrid system.

organization of the experiment is shown in Figure 9.

2.c. Methods of Examination

To make the task more difficult and challenging, the disturbance is applied as a wind (random variable) blowing up and down (perpendicular to the horizontal portion of the flight path) to make the simulated aircraft deviate from the desired path. The wind is rather realistic. Its high input power was necessary for a better analysis (50 ft./sec. peak value) to create errors sufficiently large to validate the describing function calculations.

1. The important parameters during flight that were available to the pilot to look at, are :

   a. artificial horizon

   b. angle of attack

   c. instrument sensitivity

   d. flight path as seen from the side

   e. altimeter

In addition to this set of instruments, the following parameters for display were examined:

   a. possibility of estimating the range to go

   b. possibility of estimating the proximity of the ground

   c. possibility of estimating the sink rate

2. The Pilot Performance

The pilot performance is measured from the viewpoint of ability to track the glideslope with minimum error, and

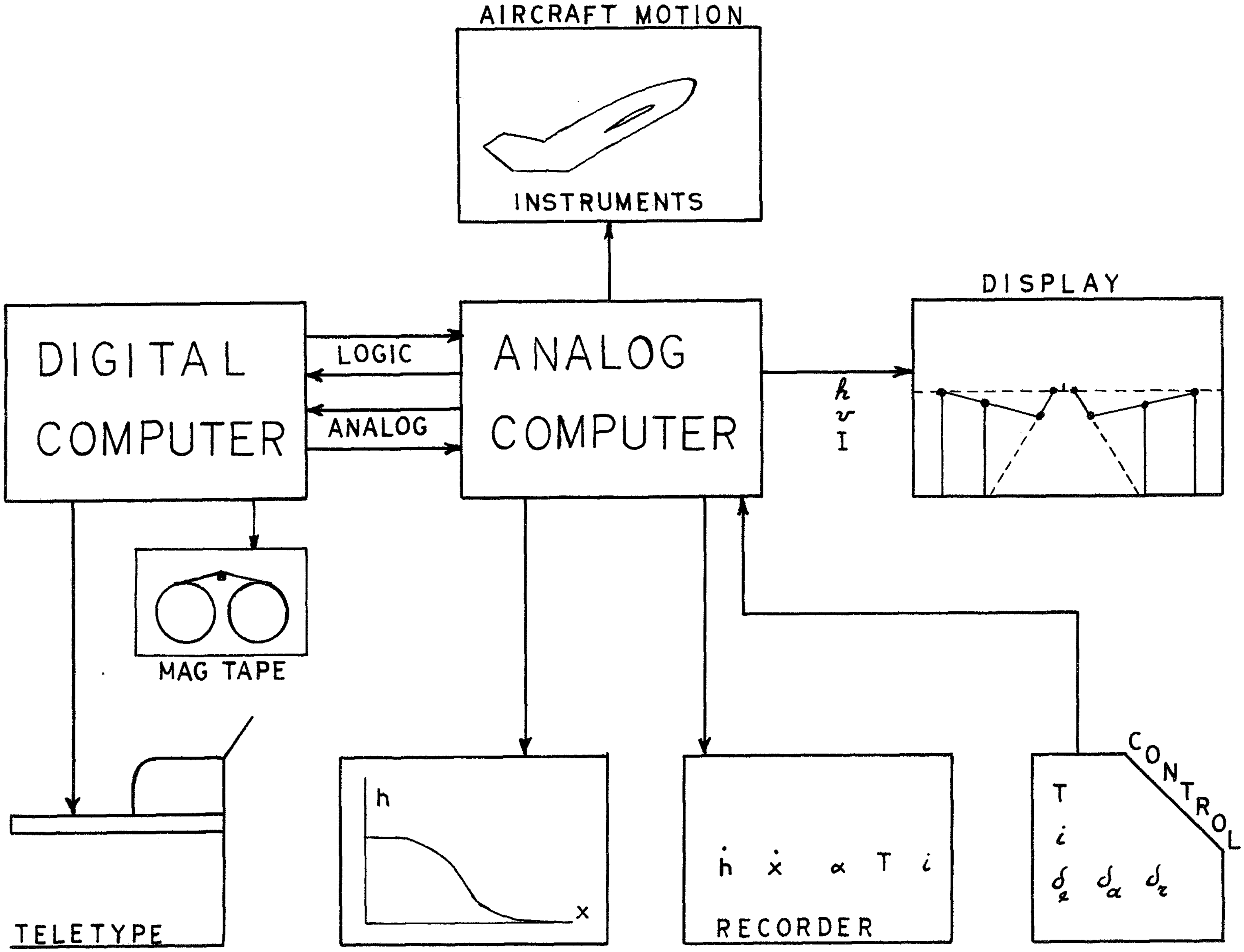


Fig. 9. The organization of the experiment.

from the viewpoint of touchdown performance: (minimum impact velocity, maximum touchdown accuracy and reasonable groundspeed).

All figures, i.e. tracking error, touchdown error, impact velocity, are weighted and added up in a score factor, which decreases for improving performance. The score factor is plotted as history of the number of trials and this plot is analyzed. A smooth and continuous curve, fitted through the data points has the following distinct features:

a. steady state level

After several trials, the pilot reaches a plateau in his performance. The lower the score factor, the more effective the system "display-pilot" is.

b. training

During the initial stage, the pilot becomes better and better in the task. The improvement observed in his learning curve is the amount due to training. The time from first contact with the system to reach the steady state ($\pm 5\%$) will be called the learning time and is proportional to the time constant of the learning curve (approximating, the learning curve as an exponential).

c. fatigue

It is quite understandable that after some time the pilot has reached his optimum, and thus his performance will deteriorate gradually with repeated trials for the same experiment. This deterioration is due to fatigue, physically or mentally, and is observed in longer reaction times, decreasing alertness, etc.

3. The Piloting Technique

The overall system was studied from the frequency response point of view, with conventional methods using the frequency domain, root locusplot and describing-function theory. The quasi-linear describing function for the pilot was evaluated for each of the different conditions, and a general idea is obtained on how well the pilot was able to stabilize the system, i.e. how much "lead" he generates in this underdamped system.

All of this information was compiled for the different classes of pilots, for each of the glideslopes and for the different display conditions. The information obtained from the experiments is summarized by the following items:

a. the touchdown consistency (mean and variance of touchdown range and speed)
b. the tracking ability (the integrated weighted glideslope error)
c. the learning curve
d. the pilot's ability for lead generation

A special note regarding the pilot opinion and the Cooper rating is given in Chapter 5.

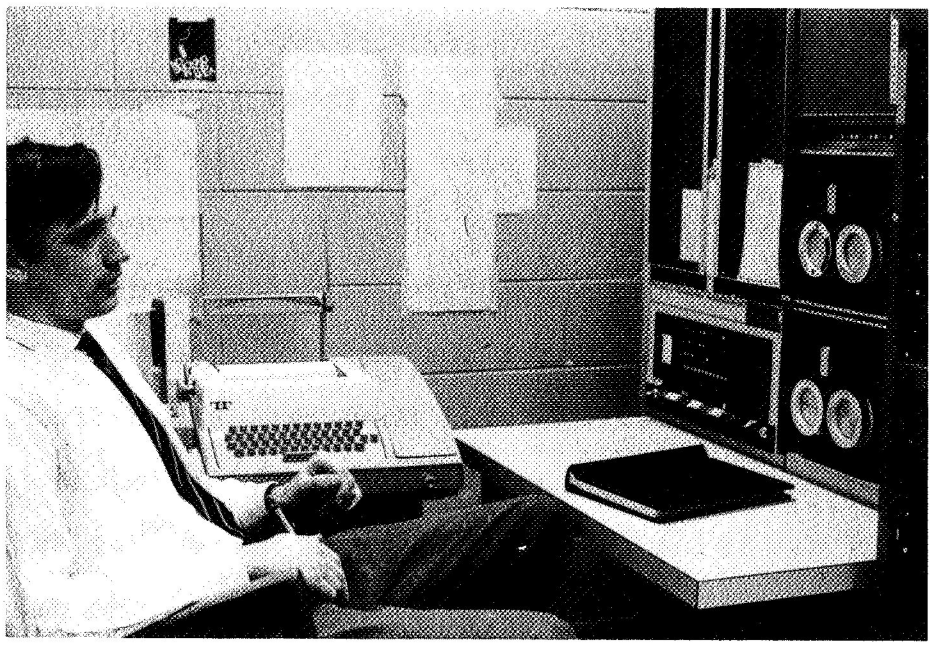


Fig. 10. The output devices in the experimental set-up : the teletypewriter and two DEC-tape drives.

2.d. Measurements

Data was measured on-line during the experiment. Data for the performance measurement was collected at a rate of 16 samples per second. This yielded the tracking score. At the end of each run these data were printed by the teletypewriter (Fig. 10). In addition to the tracking score, the touchdown performance was printed out. During this operation, the subject could rest. These figures were told to the pilot, and they were also used to look for a steady state level of performance.

Data for studies of the describing function were collected at a rate of 8 samples per second. They were first stored in a memory data buffer. When the data buffer was full, it was recorded on magnetic DECtape, while another data buffer was being filled. When the latter was full, the roles of the buffers were switched again. The data stored on magnetic DECtape were later used for data reduction.

A description of the methods and the operation of the program is given in Volume 3.

2.e. Experimental Procedure

1. The task of the pilot in the experiment was to start from an initial altitude (h_i) and fly the V/STOL aircraft (tilt-engine) level for a first period (10,000 ft). The next period (80,000 ft) is the glide along the prescribed glideslope. Near the end of this period, the pilot executed

a transition and finally got to touchdown, hopefully with maximum touchdown accuracy and minimum touchdown velocity.

2. At the beginning of the experiment, the inexperienced pilots got about five familiarization runs, the medium trained pilots got three, and the well-trained pilots none. After the familiarization runs, data were collected. For the first three runs (two for the well-trained pilots) no disturbance was applied. The average of the scores obtained in these runs was an indication of their performance ability. After these initial data runs, the wind disturbance was applied to the system. The gain was different for each category: k = 1 for the trained pilots, k = .6 for the medium trained and k = .3 for the inexperienced pilots. The length of these sessions lasted until a steady state performance was noticed and was stopped when fatigue was observed.

3. Whenever equipment malfunctioning was observed, the run was aborted and the subject was informed about the malfunction. The data collected were disregarded and the next experiment was entered with the trial number of the aborted run.

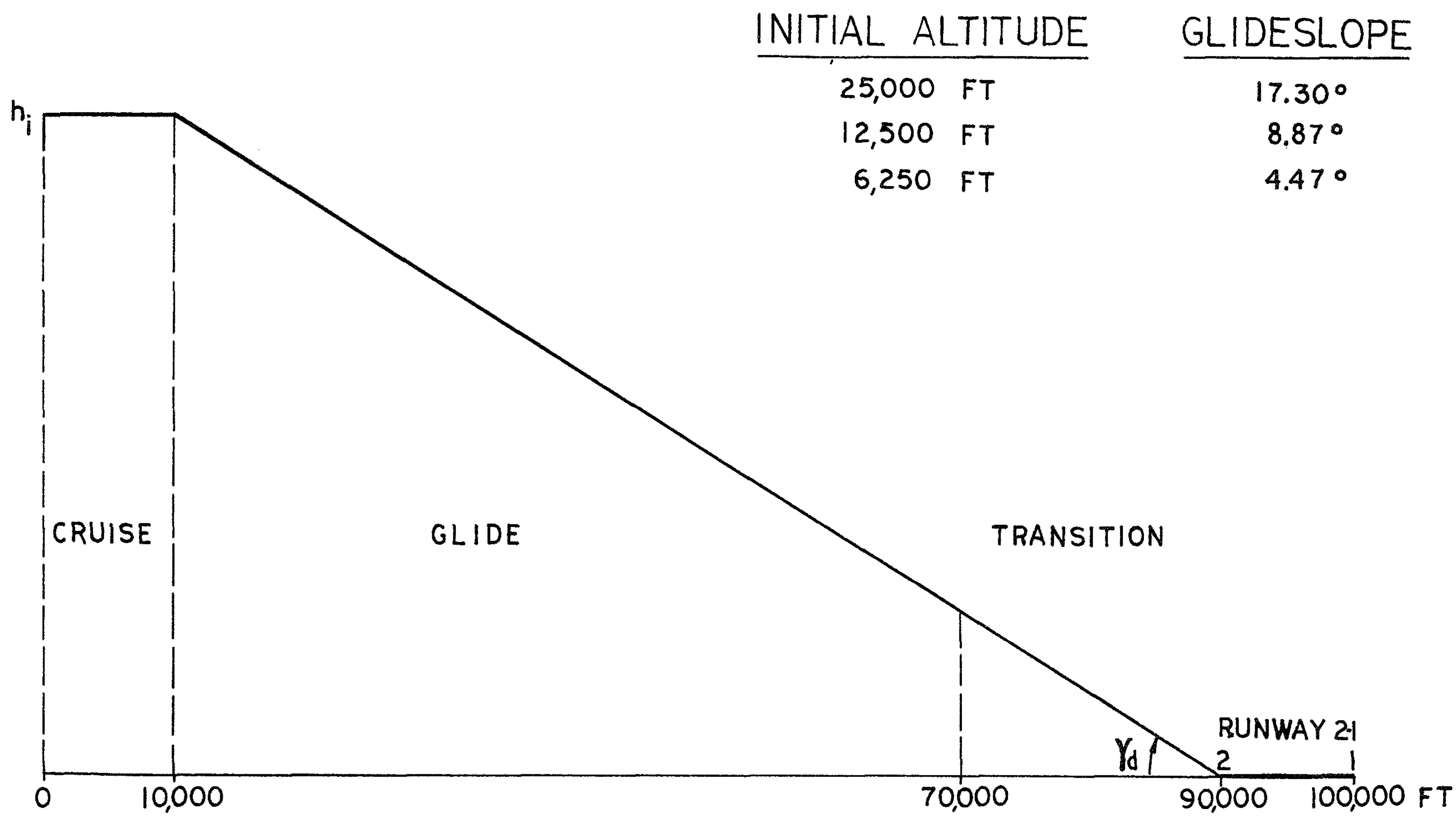


Fig. 11. The task in the experiment : cruise - glide - landing.

2.f. Pilots

To test the population of the pilots, three distinct categories of people have been used in the experiments:

a. Subjects (3) who were able to control dynamics of various order, but did not have any previous piloting experience (neither simulator nor real aircraft).

b. Pilots (2) who had experience flying a private airplane. They logged respectively 50 and 200 hours of flying time and they have been exposed to simulators.

c. Pilots (3) who although full-time students at M.I.T., while participating in the experiment, were well specialized. All had instrument ratings, and two had accumulated more than 2,000 hours each and had flown jet aircraft. One had a helicopter rating. Both had extensive experience in fixed-base simulators. The third, a female, with 300 hours had never been exposed to simulators, but at the time of the experiment, was regularly flying several hours a week and did aerobatics. She was able to do so with the simulator, too!

The pilots were briefed on the overall research program, but the criteria used were not explained in detail. This would otherwise have affected their strategy. Their comments were written down and suggestions for improvements of the setup with respect to interpretation and understanding were implemented as soon as it could be done.

CHAPTER 3

THE PERSPECTIVE GLIDESLOPE INDICATING SYSTEM

3.a. The Display Concept

The clue for the contact analog display is the "integrated picture" of the motion of the aircraft with respect to the real outside world. This situation is visually far more compelling, for example, than an integrated display where all information is simply put together on one screen. The contact analog display can differ considerably depending on the pictorialism that is added in the picture, although it is strictly speaking not necessary. Contact analog displays severely lack quantitative information, however (Ref. 80).

The present perspective display is composed only of straight lines. It is a "skeleton-type" display and it is the view one would get through the windshield of the aircraft if there were indeed a glideslope "roadway in the sky." A sketch, not to scale, is given in Figure 12 and is the view one gets at the start of the simulation. The picture is symmetrical when flying only in one plane and has, at the far end, the two parallel runway lines. The theoretical intersection of these two lines (1,2) is the horizon. The two vertical poles (3,4) are set at 20,000 ft. from the runway threshold and are an aid in indicating the beginning

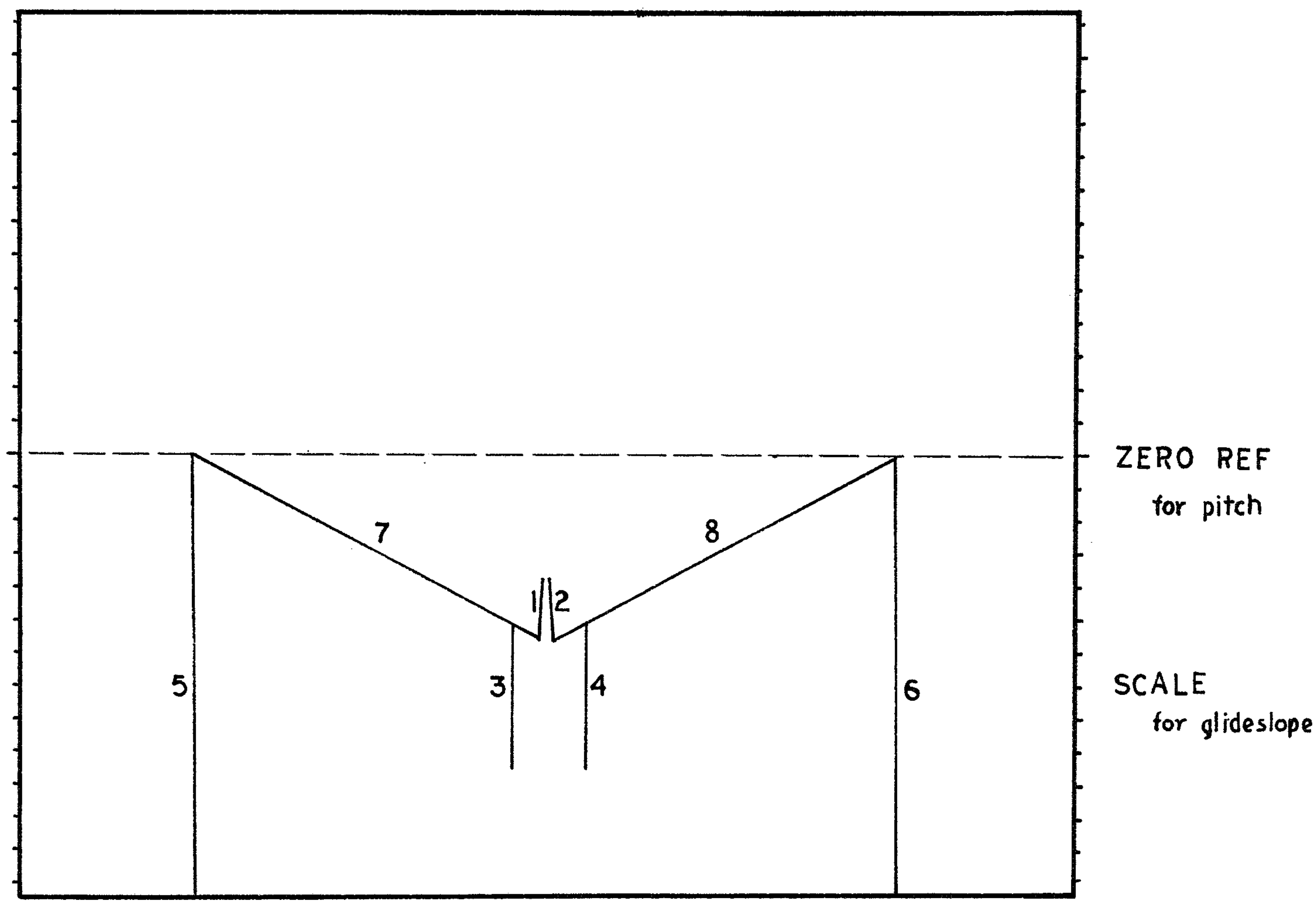


Fig. 12. The perspective display : scheme one.

of the transition in the flight. The two nearest poles (5,6) are set at the beginning of the glidepath. The glideslope itself is given by the lines (7,8) which intersect the ground plane at the runway threshold. For the first part of the flight (level flight) one must keep the top of the nearby vertical poles on the reference to get to the glideslope. The lines (7,8) at first indicate that one is too low with respect to the glideslope. They will become more and more parallel , indicating one is getting to the glideslope. Once they are parallel one keeps them that way, and learns immediately where to put the runway on the screen to stay on the glideslope. At the time the lines (3,4) come by, one starts the transition to landing, still trying to stay on the glideslope. Closer to the ground the runway lines (1,2) will spread open and at touchdown they both become horizontal. A sequence of different views along the flight path is given in Figure 13, while Figure 14 illustrates the change of aspect as seen on the screen.

The advantages of the display at first glance are:

1. Coordination in maneuvers is improved.
2. One is able to visualize rates of change of the variables.
3. In an emergency, one immediately "gets the picture" of the difficult situation.

A more detailed discussion and quantization of the display parameters is given in the results.

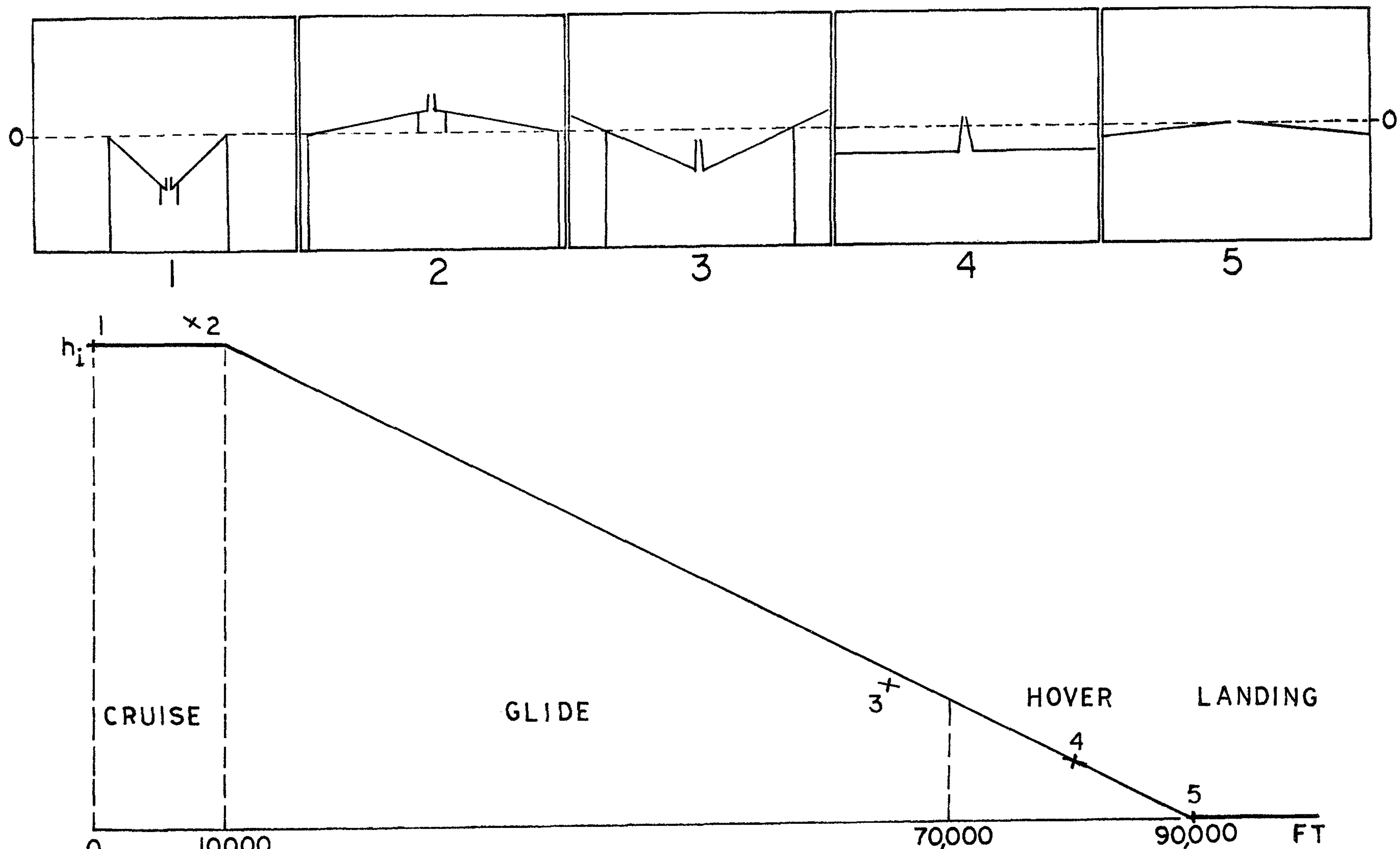


Fig. 13. The different views as seen from the indicated positions.
(It is assumed that one is on the localizer beam.)

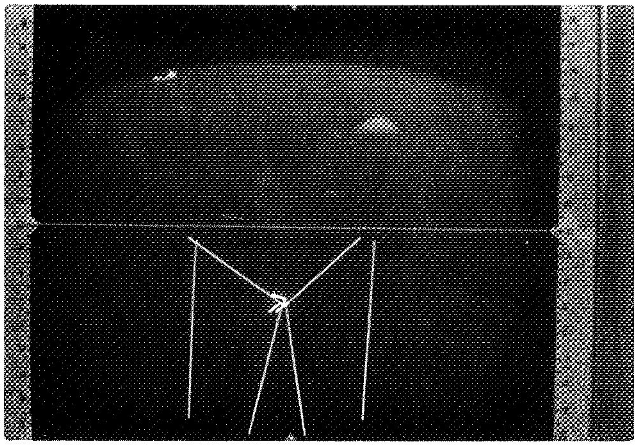


Fig. 14a. Original display concept, as seen at the start of the simulated flight.

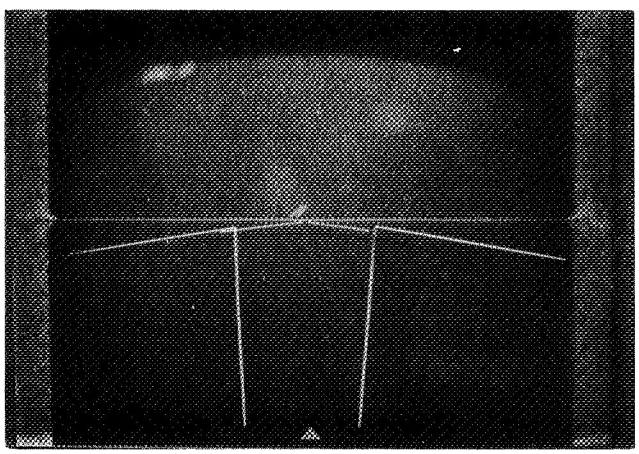


Fig. 14b. Original display concept, as seen little before the 70,000 ft marker. The aircraft is a little above the glideslope, and the nose of the aircraft is aimed at the runway threshold.

From the very first trials, the pilots were able to suggest significant improvements on the initial display format as just described, while taking into account the limitations presently imposed by the system (limitations of memory and computation) namely: only twelve points and ten lines.

The following modifications were made:

- The ground lines of the runway were extended all the way to improve judgment of proximity to the ground plane.
- The runway lines themselves were drawn as a cross, and the intersection indicated the middle of the runway. This allows the pilot to more easily visualize the distance he has travelled down the runway. This improved picture is shown in Figure 15.

A sequence of pictures as seen while going down the glide path is given in Figure 16. It should be made clear that this new form of the picture is not a final one, nor the complete one. The changes are made to investigate the improvement of the performance, for a given change in the line pattern. The present limitation of the number of lines and points severely limits us in exploring all the fine details that can be added to this perspective display. Special remarks in this respect are given in the discussion of the results.

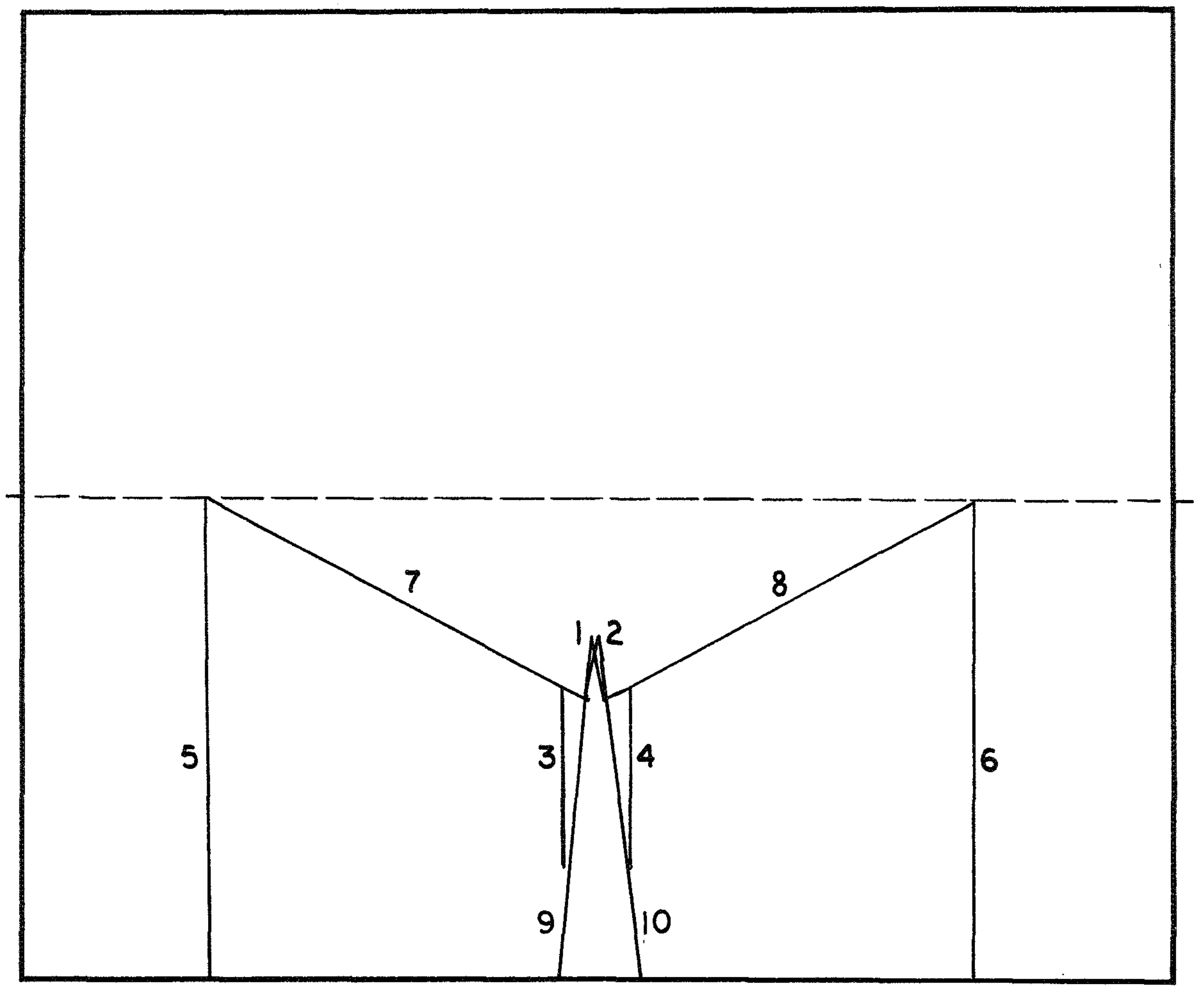


Fig. 15. The perspective display : scheme two.

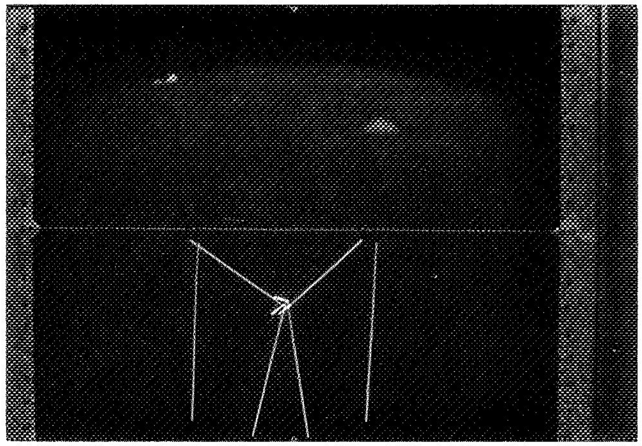


Fig. 16a. The improved display concept, as seen at the start of the simulated flight. It has the ground lines extended.

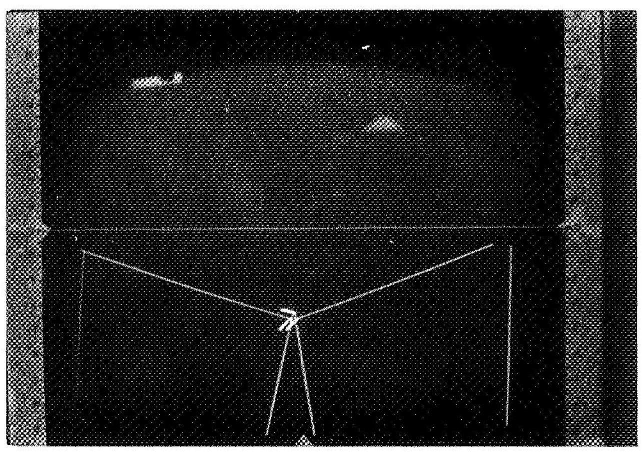


Fig. 16b. The display as seen just before the marker placed at 90,000 ft.

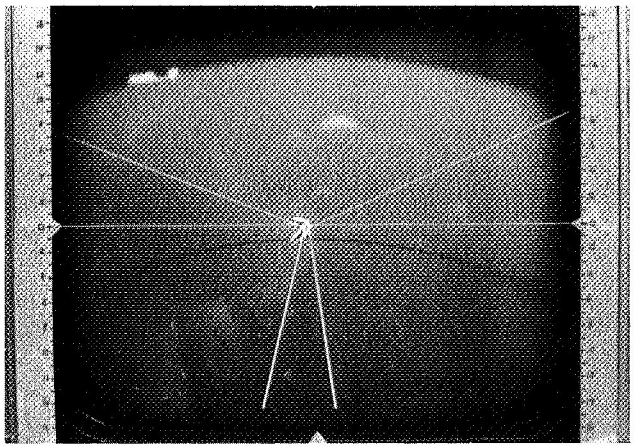


Fig. 16c. The display during the glide : the aircraft is far below the glideslope, namely 500 ft, at an altitude of 9,000 ft and 60,000 ft from the runway.

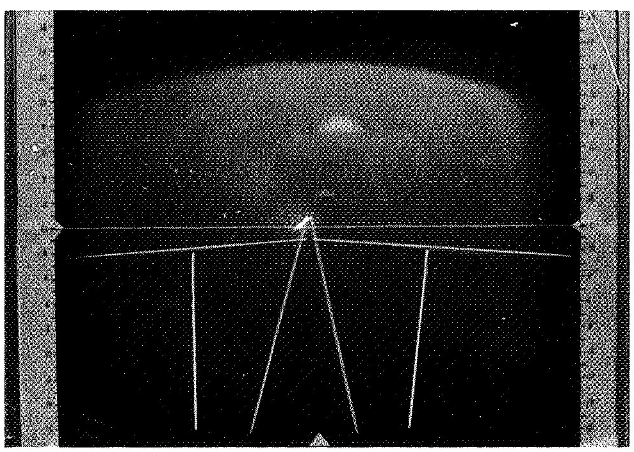


Fig. 16d. The display as seen just before the marker placed at 70,000 ft. The aircraft is a little above the glideslope, and the nose of the aircraft is aimed at the runway threshold.

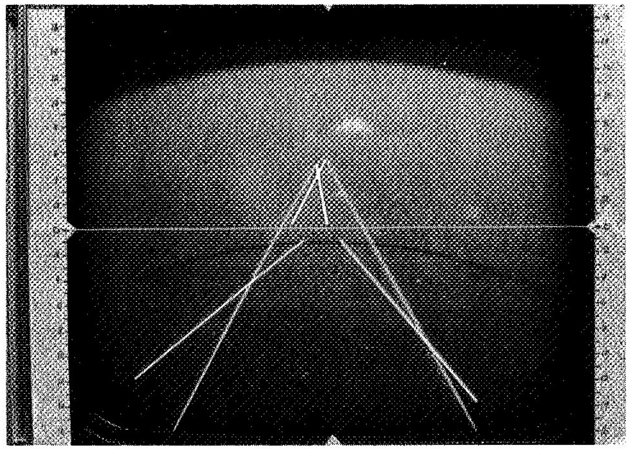


Fig. 16e. The display as seen during hover at 5000 ft from the runway. The aircraft is high above the glideslope, and the nose of the aircraft is aimed at the runway threshold.

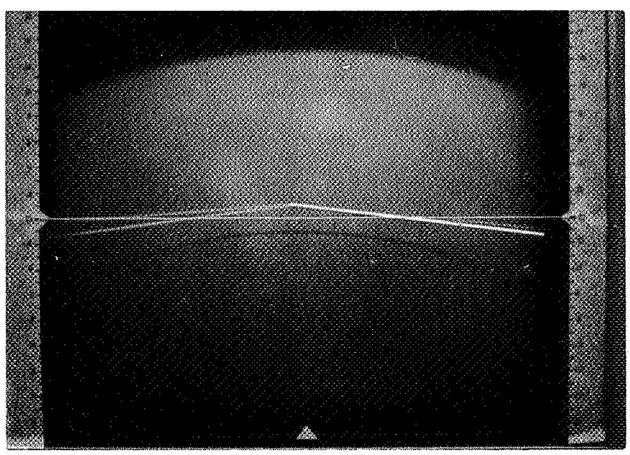


Fig. 16f. The display as seen seconds before touch-down. The nose of the aircraft is aimed at the far end of the runway.

3.b. How to Read the Display

Quite a number of variables (attitude, velocity, position) are incorporated in one single display consisting only of a few lines connecting distinct points. It is, therefore, important to be able to derive the information properly from a highly compact though not cluttered display. The following description indicates how to derive the available information:

1. The Glideslope Error

When one is right on the glideslope, the glideslope lines make one straight line. In the event one is too low, the glideslope lines are bent upward*: the closest points of the glidelsope (near the edge of the screen) are above the horizontal reference line, indicating that the plane's reference line is lower than the glidelsope reference. On the other hand, being too high above the glideslope will be indicated by the lines going down, from the center to the side.

2. The Glideslope Error

When one is perfectly aligned with the runway, the picture is symmetrical. If one is (too much) to the left of the glide path, the leftmost glideslope line will tend to be foreshortened, and the extended groundlines will run off the bottom screen edge to the right. Similarly, if one is too much to the right of the glide path, the extended ground lines will run off the bottom screen edge to the left.

*as though one were looking up at the underside of the roadway.

3. The Attitude

Attitude indication is provided by the far end of the scenery, i.e. the end of the runway, in theory the horizon of the intersection of the parallel runway lines. In practice, coming down the glideslope one is interested in the pitch attitude as well as in roll. Close to the ground heading becomes important since runway alignment is a necessity. Both scales in pitch and yaw are equally sensitive. Pitch changes where the point at infinity for a given direction moves from the center of the screen down to the bottom where it corresponds to 22.5° nose up while moving the nose down 22.5° brings that point to the top of the screen. Yaw changes of 22.5° to the right make that point move to the left edge of the screen while 22.5° to the left brings it to the right egde. Roll is derived from the rotation of the scenery and has a unit gain. A 90° of roll, for example, brings the vertical poles horizontal. Accurate roll readings are derived from the assymetry in the picture.

4. The Altitude

No accurate scale is provided for altitude readings. Only two heights are of importance: the immediate vicinity to the ground, and the error from the desired glideslope. The effect of non-linear gain makes it extremely useful to estimate altitude deviations from these two reference altitudes.

5. The Range to Go

The distance to go to the runway follows directly from the picture. An accurate reading is not necessary, but distinct distances are indicated by vertical poles, located at well-known distances from the runway.

6. The Velocity Indication

Initially, it was hoped that forward velocity could be provided by the motion of the vertical poles, but this was soon ruled out.* Their motion is an effective cue only when the aircraft is close to the poles. Therefore, groundspeed has been indicated using a separate instrument and this was the only instrument used besides the display. Vertical speed indication, on the other hand, is derived from the moving picture and is determined by the groundspeed and the glideslope. Close to the ground more effective indication is given by the aspect of the changing ground and runway line 2. Besides the straightforward derivation of the status information, the unique quality of the display is that it shows in a convenient way the rates of change of parameters and this way it has so-called short-term prediction qualities. The general rule using the display and reading it, is that position indication is gotten from the lines at the edge of the screen for points close to the screen while the attitude of the aircraft is derived from that part of the picture which represents the most distant

*Their motion is disturbing, rather than helpful.

points in the scenery. The velocities then are derived from the motion of the nearby part of the lines, while angular velocities are gotten from the motion of the distant parts of the picture. The latter information helps in reducing the g-forces on the wings while changing the pitch attitude of the aircraft.

It was not advisable to include a groundspeed indication on the display itself because the positive or negative sense could not be represented in a unique and non-conflicting manner. It is a quantity which strictly speaking, cannot be represented in a vertical bar display with the proper dimension in its proper direction.

3.c. Display Set-Up: Equations

This contact-analog display is of the "skeleton type" and consists of straight lines, connecting characteristic points. The two basic parts in the generation of the display are:

1. the digital portion which does the accurate computation
2. the analog portion, which is the line drawing mechanism

Details of these operations are described in Volume 2, and only the basic elements of the computation will be discussed below.

3.c.1. The digital computation consists of two parts:

1) an inertial update for the points using the information related to the aircraft motion (the change in position and the attitude change)

2) the perspective transformation, which is done for each line

The lines are determined by a list of display points. This list can be modified quite rapidly, according to the application.

1. The coordinates of the points are stored in an inertial list. (This list is called from a permanent inertial list, at the start of the experiment.) The list contains the three coordinates of each point. The points are stored sequentially. Each coordinate has triple precision significance and each part is called a high, a medium and a low order part. The list is organized as follows:

$$X_{O,H}\ X_{O,M}\ X_{O,L}\quad Y_{O,H}\ Y_{O,M}\ Y_{O,L}\quad Z_{O,H}\ Z_{O,M}\ Z_{O,L}$$

$$X_{1,H}\ X_{1,M}\ X_{1,L}\quad X_{1,H}\ \ldots.$$

These coordinates are defined in aircraft body axes.

2. The aircraft moves about and the coordinates change. This information is given by a translation along the three axes, and a rotation about the three axes of the body frame. The translation used in the program is derived from the inertial translation of the aircraft and transformed

into body axes. The rotation is provided by angular velocities and is derived from the change in attitude of the aircraft. The quantities used are:

Δx, Δy, Δz and $\Delta\phi$, $\Delta\theta$, $\Delta\psi$

The coordinate changes due to translation are obtained in the following way (going from position 1 to 2)

$$\bar{R}_2 = \bar{R}_1 - \bar{U}\,\Delta t \qquad (1)$$

$\bar{R}_2$: vector for position 2, resolved in body axes

$\bar{R}_1$: vector for position 1, resolved in body axes

$\bar{U}$: velocity* vector resolved in body axes

Δt : elapsed time, between positions 1 and 2

and

$$\Delta\bar{R} = -\bar{U}.\Delta t \qquad (2)$$

Appropriate scaling decreases substantially the mathematical operations involved. For this reason the time Δt is always a binary fraction of a second: $\Delta t = 2^{-x}$ ($x = 4$ in this experiment).

The coordinate changes due to rotation (between situation 2 and 3):

$$\bar{R}_3 = T\,\bar{R}_2 \qquad (3)$$

where $\bar{R}_3$: coordinates resolved in the rotated frame

$\bar{R}_2$: coordinates resolved in the original frame

T : transformation matrix

This transformation matrix is approximated rather than using the sine- and cosine-values. The method used and the order of this update procedure is explained in more detail in

* Velocity of the aircraft with respect to an earth fixed frame

Volume 2.

3. After the coordinates for one point are updated, they are stored in their original place, thus saving space but not affecting further computations.

4. Once all the points are computed, the perspective is derived for each individual line. The line identification is stored in a line list and is characterized by the end points. Each end point is described by two digits. This list looks like:

0001: connect point 00 with point 01

0110: connect point 01 with point 10_8

5. The equations for the perspective transformation are (Fig. 17a) :

$$h = \frac{Y}{X} d \qquad v = -\frac{Z}{X} d \tag{4}$$

where h, v : the screen coordinates (horizontal and vertical deflection)

X,Y,Z : the coordinates of the point

d : distance between observer's eye and the screen

In the case of the screen being tilted, at an angle ν, (Fig. 17b) then these equations are:

$$h = \frac{Y}{X \cos \nu + Z \sin \nu} \qquad v = \frac{X \sin \nu - Z \cos \nu}{X \cos \nu + Z \sin \nu} \tag{5}$$

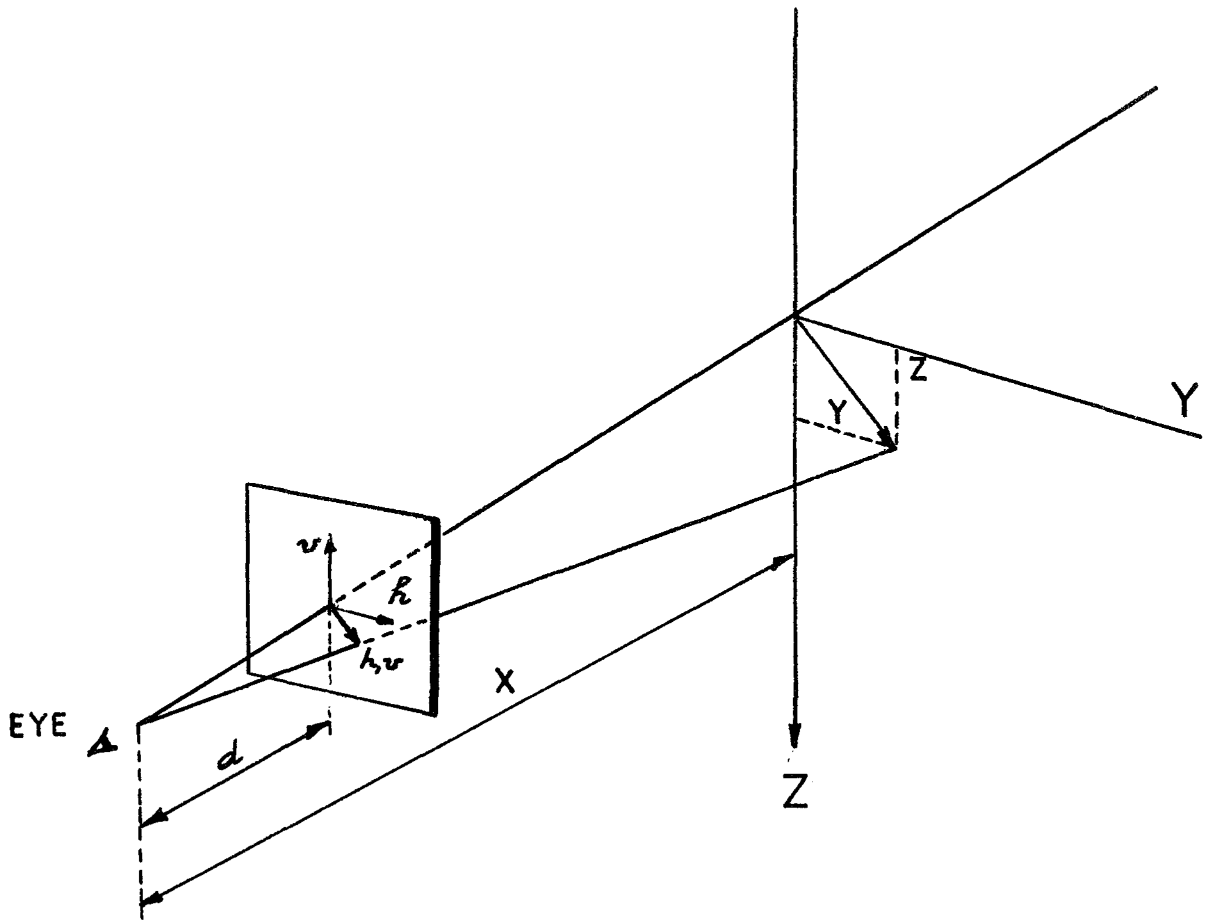


Fig. 17a. Definition of the coordinate systems.

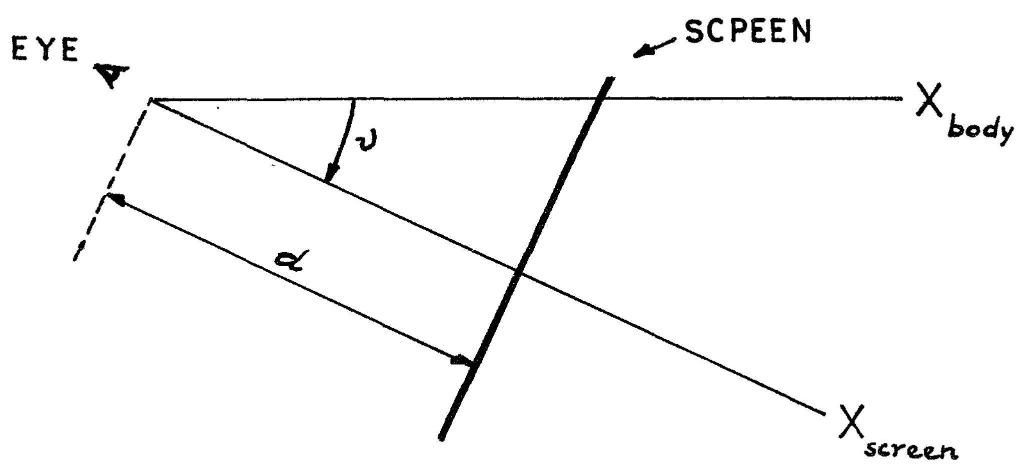


Fig. 17b. Definition of the screen coordinate axes for a tilted screen.

For $X \leq 0$ the formulas do not hold any longer, and a limitation technique must be applied if part of the line is seen. The limitation to the plane of the screen yields:

$$
\begin{aligned}
X_2' &= 0 \\
Y_2' &= Y_1 + X_1 \frac{Y_2 - Y_1}{X_2 - X_1} \\
Z_2' &= Z_1 + X_1 \frac{Z_2 - Z_1}{X_2 - X_1}
\end{aligned}
\qquad (6)
$$

where 1 is the point in front of the screen

2 is the point which $X_2 < 0$

Not all points with $X > 0$ are visible, but only those in the solid angle determined by the screen edges, with the observer's eye as apex. For a circular screen, this view angle is a circular cone determined by a constant angle. The present application uses a visual half angle, $\eta = 22.5°$. Points outside this cone are limited using the formula:

$$k = \frac{X_1 \tan \eta - R_1}{\Delta R - \Delta X \tan \eta} \qquad (7)$$

where

$$
\begin{aligned}
R_1^2 &= Y_1^2 + Z_1^2 \\
\Delta X &= X_2 - X_1 \\
\Delta R &= R_2 - R_1
\end{aligned}
$$

which yields:

$$
\begin{aligned}
X_2' &= X_1 + k \, \Delta X \\
Y_2' &= Y_1 + k \, \Delta Y \\
Z_2' &= Z_1 + k \, \Delta Z
\end{aligned}
\qquad (8)
$$

These new coordinates are then used in the perspective transformations. It must be emphasized that these formulas do not involve approximations, because of the linear character of the operations in the limiting algorithm. Hence, the location of the line on the screen is exact and allows a correct read-out whenever this is desired.

6. Besides the two coordinates h, v for the two end points of the line, a third coordinate is computed, namely an intensity coordinate. These lines are drawn during a constant time interval T. Hence, short lines look brighter than long lines. To modify the intensity of the oscilloscope beam, the grid voltage is changed according to the line length. This formula is (Ref. 140):

$$V = C_1 + C_2 \, L^{2/3} \tag{9}$$

where V : voltage at the grid (in volts)

C_1, C_2 : characteristic constants for the oscilloscope

L : line length (in cm)

If one wants to modify the intensity with the slant distance of the point, the author showed in Ref. (140) that:

$$V = C_1 + C_2 \left\{ L \left(\frac{D_o}{D} \right)^2 \right\}^{2/3} \tag{10}$$

where D : slant distance of the point

D_o : reference distance

The third coordinate I is then also computed at each point, using the distance or depth (D) of the point and the length (L) of the line between two visible points.

7. These coordinates are stored in a display list, in sequential order. This list is organized as follows:

$$h_i, v_i, I_i, \quad \Delta h, \Delta v, \Delta I$$

The first three quantities are the initial conditions for the line, the last three are the rates for that line.

3.c.2. The analog portion consists of two parts:

1. an analog circuit which draws the line
2. a logic circuit controlling the data transfer

A clock signal, consisting of a pulse train, has a "downtime" and an "uptime". During the uptime the drawing integrators draw the line at the rates indicated, and the beam is unblanked. During the downtime, the track and hold integrators reset, as do the drawing integrators (Fig. 18). During this reset period, the beam is blanked.

A detailed description of the circuitry is given in Volume 2.

3.c.3. The synchronization is provided by the logic portion of the analog machine, which triggers the digital program and tells it to wait, to run or to affect data transfer.

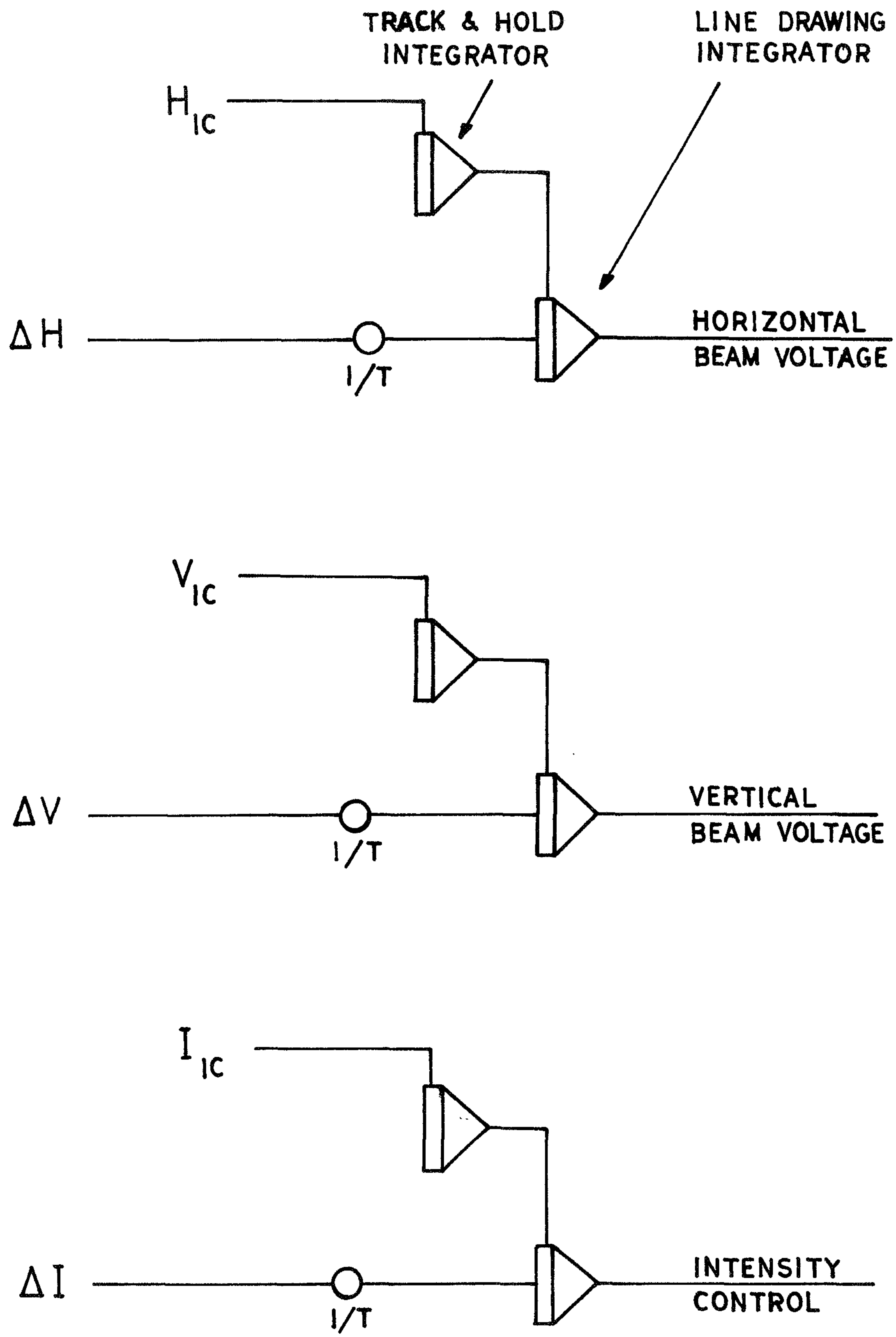


Fig. 18. Analog line drawing circuit.

3.d. Design Principles for the Display

From what has been described in the preceeding paragraphs, it has become clear that there are many variables which one must determine. Among these parameters are:

- the screen size or width : s
- the distance between the observer's eye and the screen : d
- the inclination angle : ν
- the visual angle : η
- the visual limiting distance : D_L

In addition, one has complete freedom in drawing imaginary lines (e.g. glideslope) or in changing the instrument gains (e.g. roll bar). Hence, other parameters are:

- the display gain : K
- the glideslope road width : w

A variation of one parameter sometimes does not affect one single item. To give a complete detailed list on how to choose each single parameter would be too ambitious, but some guidelines will be given here as they become understood while performing experiments with the perspective display.

1. The larger the screen, the more resolution can be obtained and the picture becomes less compact and less cluttered. However, there is a trade-off because the beam is less well defined. The <u>size</u> of the oscilloscope will

also be determined by the available space in the cockpit. It was observed during the course of the experiment, that an 8" * 10" screen was better than a 2.5" * 2.5" screen. It was also more realistic and gave a better impression of the viewer's window.

2. The distance d to the screen, viewing distance, depends upon eye accommodation and cockpit space. For conventional aircraft, it is usually 28 inches (Ref. 80); for rotary wing it is of the order of 18 to 28 inches (Ref. 80).

3. The field of view designates the solid visual angles subtended by the display. For the display, only the instantaneous field of view is considered. (Head movement as used in Ref. (140) defines the total field of view.) The visual angle 2η, used in this experiment, is 45° and follows from:

$$\eta = \text{arc tan } \frac{s}{2d} \qquad (11)$$

The symbols are defined earlier.

4. When the field of coverage is the same as the field of view, the display gain is unity. If one would show the same picture as seen at a distance d, at a distance 2d instead, the display gain is half. It turns out that the tracking is affected only slightly. This display gain does not seriously influence the performance. If one should double the roll gain, (e.g. a roll of 22.5° is indicated by roll bar

inclination of 45°) this will be referred to as an <u>instrument gain</u>. In the display, this instrument gain cannot be mixed with a different display gain without deterioration in performance.

5. While drawing the display, it is possible to control the beam intensity so that distant points become so dim that they are invisible. This visual limiting distance D_L is controlled by the reference distance D_o in formula (12). The distance D_L can be used for the following purposes:

- to determine the depth graduation between the screen (full bright) and distance D_L (dim to invisible)
- to indicate some critical distance before which special control action must be taken

The sensitivity of this factor has been reported by Ref. (140). To change the affect on the performance improvement, one chooses a different law of illumination:

$$I \sim D^{-m} \tag{12}$$

where $m = 1$ or less, instead of the inverse square law value $m = 2$. Formula (10) would then read:

$$V = C_1 + C_2 \left\{ L \left(\frac{D_o}{D} \right)^m \right\}^{2/3} \tag{13}$$

It is worth noting that it is possible to introduce a fictitious line length $L' = 2L$ to make certain lines look twice as bright.

6. Due to its nature, perspective brings along the fact that the separation of more distant points displayed on the screen is much less than for nearby points. This is referred to as <u>non-linear gain</u> of the perspective display. It is extremely useful in the display because this feature can be used to increase the sensitivity about a nominal value and to decrease the sensitivity for values which otherwise would go off scale. This will become clear from the following considerations. Suppose a line is drawn on the screen from the center horizontally to the screen edge; the line can be represented by the parameter equations $(h_o = v_o = 0)$:

$$\begin{aligned} h &= h_o + kh_1 = kh_1 \\ b &= v_o + kv_1 = kv_1 \end{aligned} \tag{14}$$

where h and v for each point follows from equation (4). Then at the edge of the screen, $h = h_s$. Transformation of equation (14) with (4) yields:

$$k = h_s \frac{X}{Y} \tag{15}$$

and also:

$$v = -h_s \frac{X}{Y} \frac{Z}{X} = -h_s \frac{Z}{Y} \tag{16}$$

Hence, the change in displacement (Δv) at the edge of the screen is related to a change in altitude by the following expression:

$$\frac{\Delta v}{\Delta z} = - \frac{h_s}{Y} \tag{17}$$

This formula holds for small changes about the horizontal condition, and shows that the gain depends not only on the screen size h_s, but also on the Y-coordinate. This coordinate may be the road width of the glideslope. This shows that for a 10" screen (h_s = 5"), a roadway in the sky, 1000 ft wide, and a minimum resolvable offset of the line on the screen of 2.5 mm (1/10"), one observes an altitude deviation of 10 ft! When the same line becomes vertical, the sensitivity to altitude change becomes zero:

$$\frac{\Delta v}{\Delta Z} = 0$$

However, the reading at the bottom edge of the screen indicates:

$$\frac{\Delta h}{\Delta Y} = \frac{v_s}{Z} \tag{18}$$

and the smaller the altitude Z with respect to the reference, the higher the sensitivity is for lateral offset.

This non-linear gain feature is useful for tracking the glideslope if the glideslope lines are drawn, or for coming in for a landing when the ground lines are drawn. The latter case takes advantage of both altitude estimation and lateral displacement.

7. Finally, there is the picture structure which is important. The lines chosen must each fulfill a special role. For instance, it is possible to display a line, to indicate a given distance to go, or it is possible to draw the runway as a cross, to indicate the center of the runway.

Some feeling is required on what additional lines to choose and in quite a number of cases the performance of the aircraft will give indications in which directions the design should go.

CHAPTER 4

EXPERIMENTAL DATA AND RESULTS

A brief summary of the results is given in Chapter 1 and 6. The following chapter gives a detailed description of the data available from the experiments as well as the results derived from this investigation. A complete documentation of the data contains tables and charts. These data are the result of more than 1000 simulated landings.

4.a. Description of the Records

4.a.1. During the experiment, two kinds of recordings have been made. They are:

- an X-Y chart of the flight path
- the time-histories of five variables

a. The X-Y chart of the flight path (Fig. 27) gives the altitude versus the range. The scales have been worked out so that the plotted initial altitude was always the same, namely, 2.5" for 25,000 ft. (steep), or 12,500 ft. (medium), or 6,250 ft. (shallow glideslope). In one plot, there are plotted 10 runs to work efficiently. The order is from bottom to top. The figure shows that the first three runs have been familiarization runs, while from the fourth one on the wind disturbance was applied. Note that as time goes on this pilot's tracking has improved.

b. The graph with the time-histories (Fig. 19) shows the following variables: groundspeed, vertical velocity, angle of attack, thrust and engine tilt-angle. The initial groundspeed is 500 ft/sec, and during the glide this groundspeed remains almost the same for the medium glideslope. For the steep glideslope, it increases but for the shallow one it decreases. This is only so when the pilot does not use the throttle. The vertical velocity at the start is zero. The plot shows that during the descent there are oscillations for an inexperienced subject (Fig. 19a) while there are none for the experienced pilots (Fig. 19b). However, when the disturbance is applied, the graph shows that the vertical velocity is the sum of the rate of climb and the wind disturbance (Fig. 19c). The angle of attack is given by the third trace. One observes on the plot that the smaller the velocity, the larger the angle of attack is. Timing pulses are superimposed on the plot and the time between pulses is 5 seconds. The fourth trace shows both the throttle setting on the top part, and the engine tilt angle on the bottom. The scales are indicated on the chart.

As was indicated earlier, these plots, especially the strip charts, were used to check for equipment malfunctioning. Types of malfunctioning that could occur are: hung-up integrators for deriving inertial positions, oscillatory D/A channels and dead A/D channels.

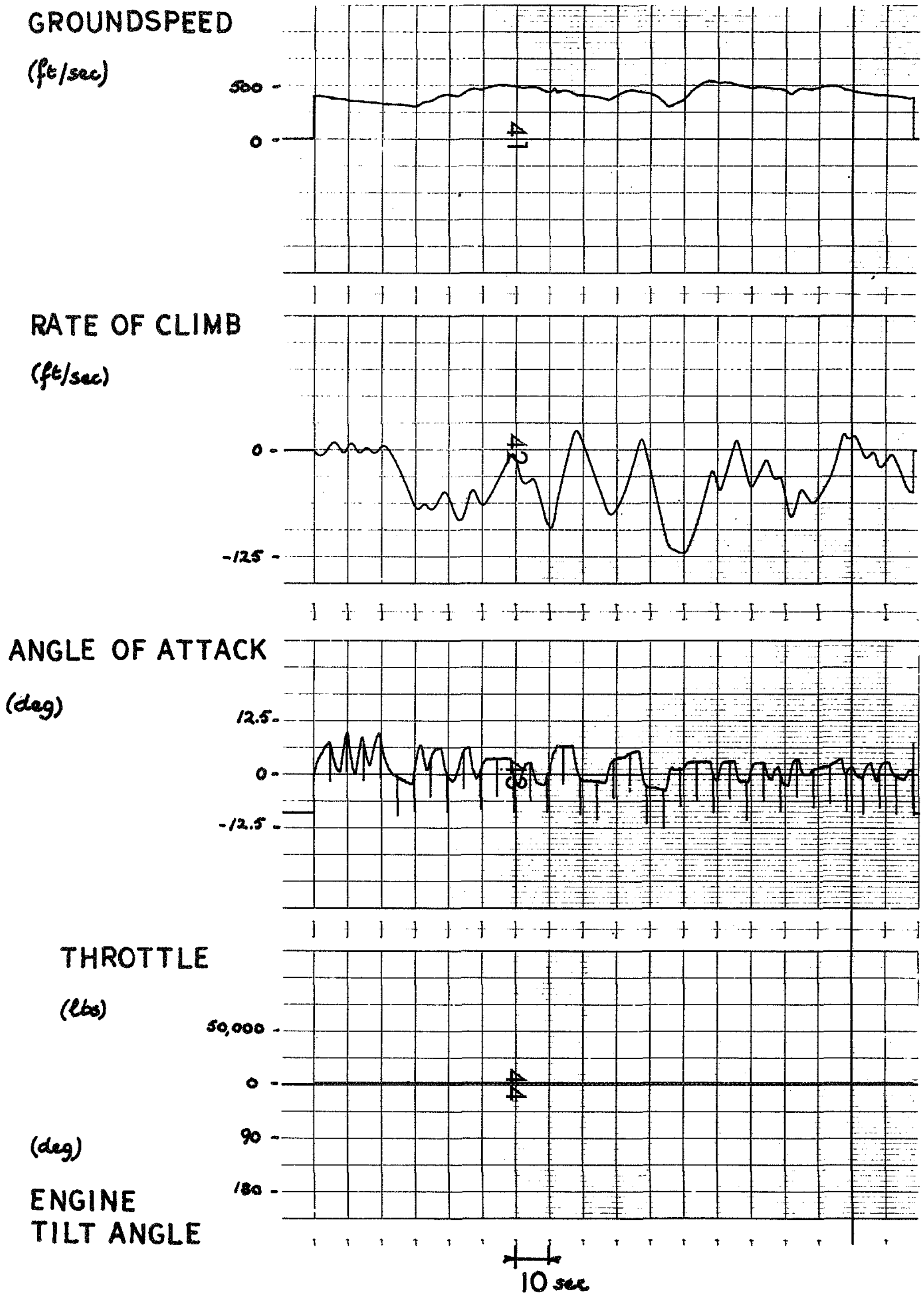


Fig. 19a. Time histories of flight variables.
Case of an inexperienced subject.

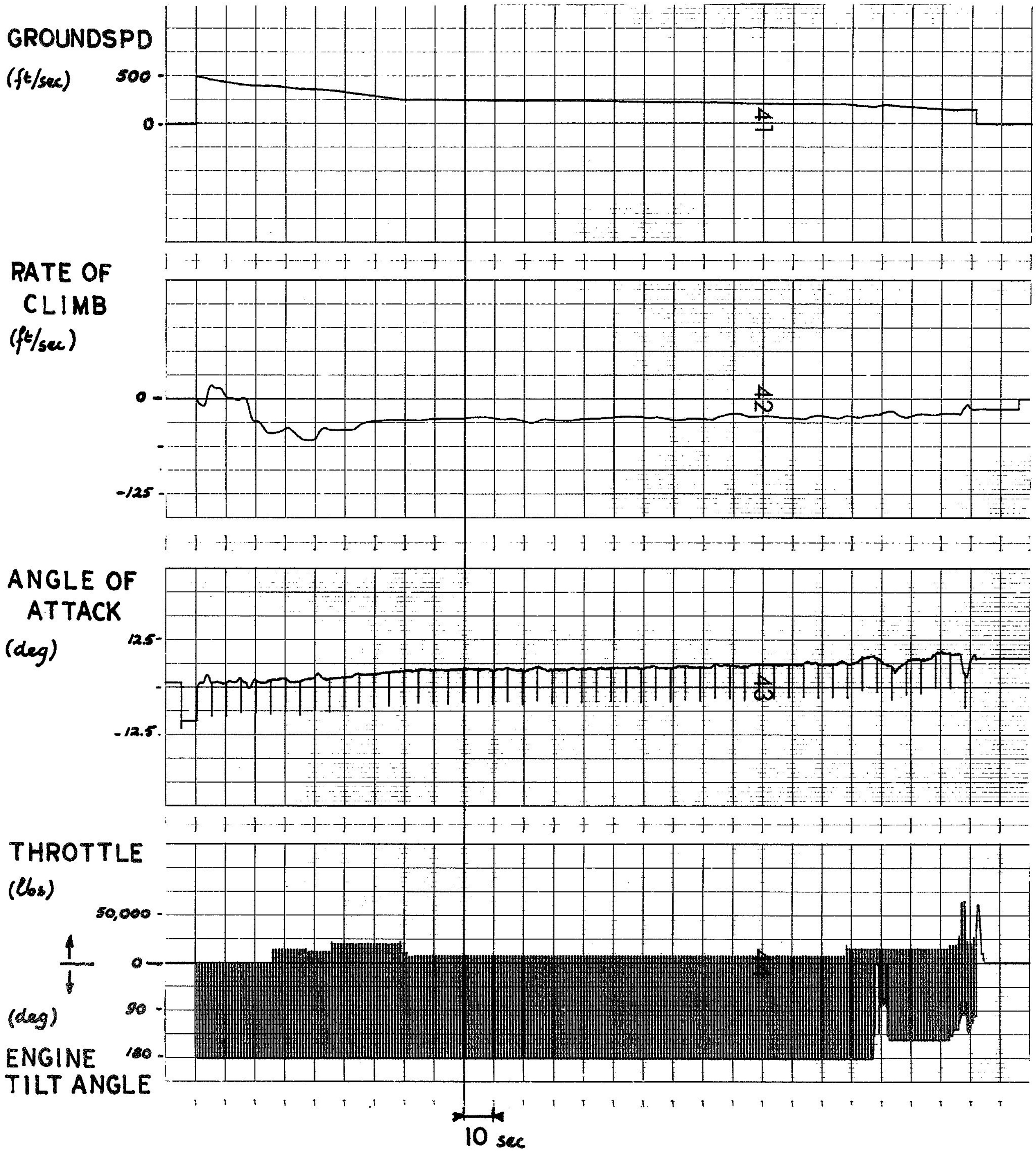


Fig. 19b. Time histories of the flight variables.
Case of a well-trained pilot, no wind disturbance.

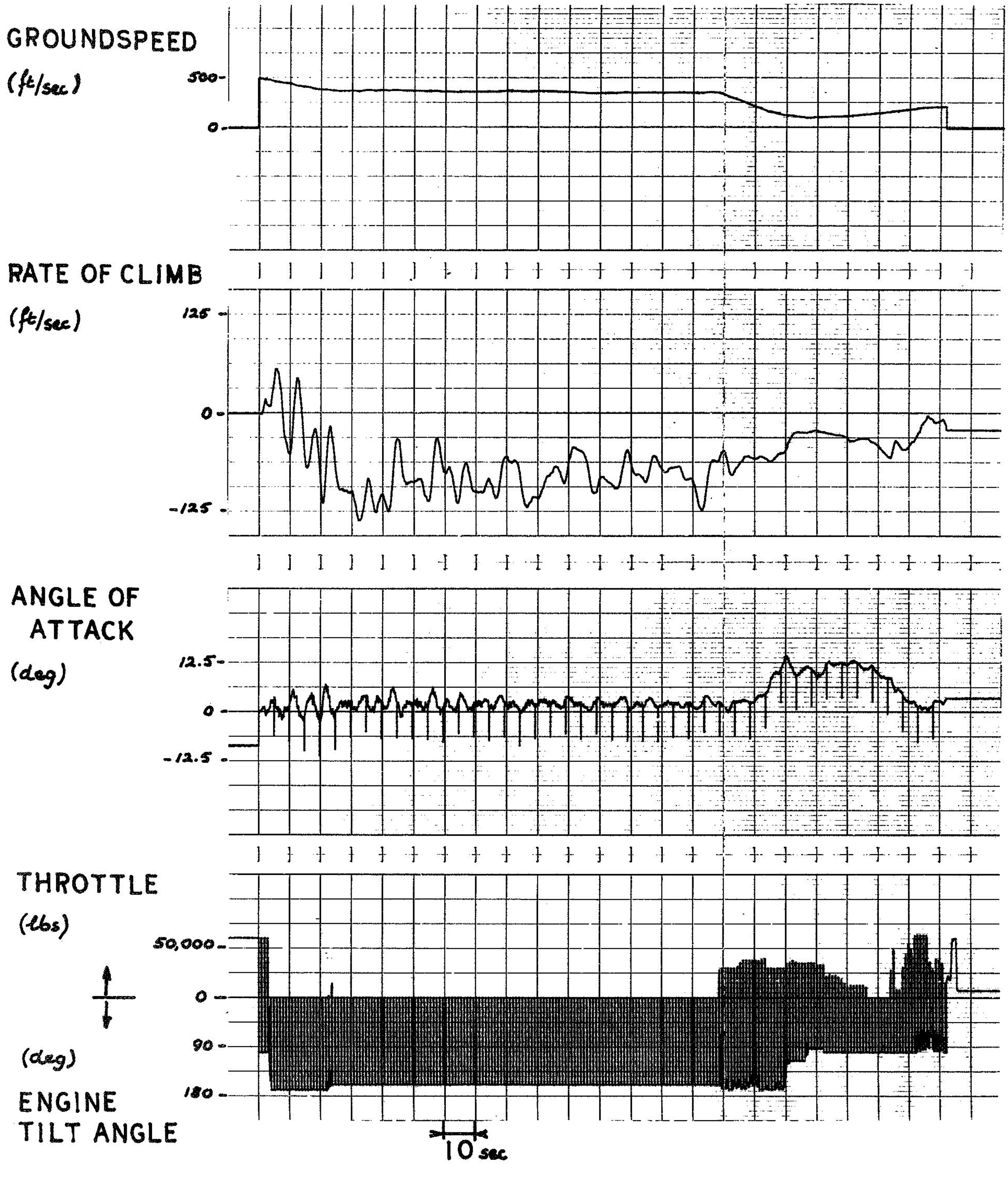


Fig. 19c. Time histories of the flight variables.
Case of a well-trained pilot, with wind disturbance

4.a.2. At the end of the experiment, a teletypewriter print-out was given which gives the tracking score and the touchdown performance. A sample of the print-out is given in Volume 2, (Fig. 10). The results given are:

- time spent in a given phase
- integral of the deviation from the prescribed glideslope
- weighted absolute error
- average absolute altitude error

The four quantities are given for each of the following phases of Figure 11.

- cruise (0 → 10,000 ft)
- glide (10,000 → 70,000 ft)
- transition (70,000 → 90,000 ft)
- landing (runway)

The three additional quantities are:

- touchdown range
- touchdown vertical velocity
- touchdown groundspeed

For the tracking, only the weighted absolute error is important.

4.a.3. While running the experiment, data were stored on magnetic DECtape (Vols. 2 and 3). These data were used to derive the pilot describing functions in the following way:

- the first relationship is:

$$\frac{\text{elevator control}}{\text{glideslope deviation}}$$

- the second one is:

$$\frac{\text{angle of attack}}{\text{flight path angle}}$$

This pilot describing function analysis was done after the experiment was concluded, and was performed as a quasi-on-line data reduction. Each run was examined separately at first, to be able to look at the change in control strategy and to correlate it with his learning behavior. Later on an averaging technique was applied.

Generation of the Bode plot for the describing function was mechanized for efficiency. A sample of the mechanized Bode plot is given in Figure 20. The top half of a combination of two graphs shows the amplitude ratio in dB, while the second half shows the phase difference in degrees for the output-input pair of the describing function. The mechanized plot is composed of selected spikes and the actual curves of the Bode plot are the envelopes of these plots. These spikes are the exact values of the ordinate (either amplitude ratio or phase difference), and they occur at the frequency indicated on the frequency scale. The frequencies of the Fourier Transform program are multiples of a basic frequency and the random input has been prepared as a sum of 20 sinusoids, whose frequencies are multiples (given by prime numbers) of this basic frequency.

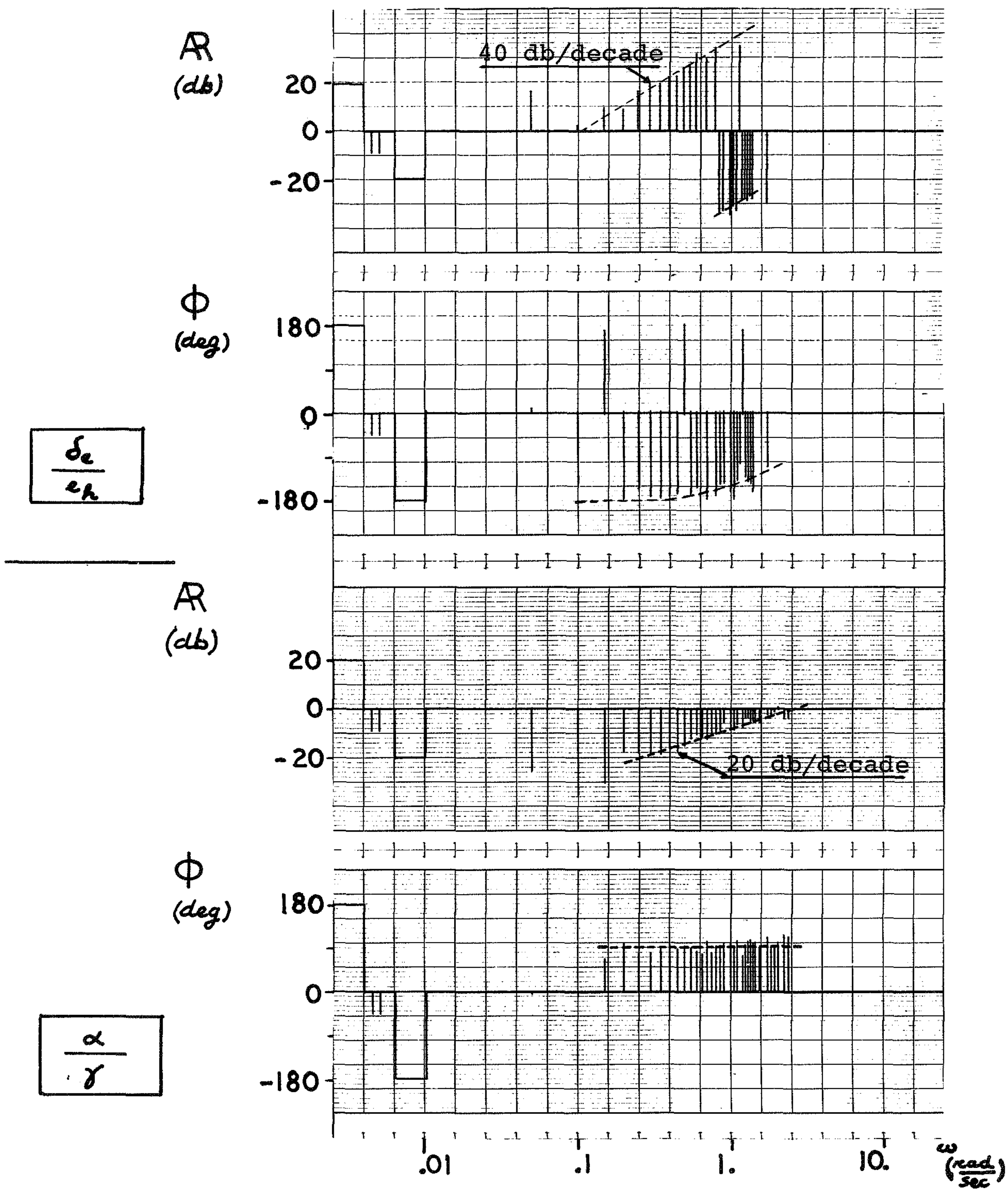


Fig. 20. Typical Bode plots, showing the pilot's quasi-linear describing function.

The plot in Figure 20 is the case of an experienced pilot, whose describing function (δ_e/e_h) is a second order lead (40 db/decade and 180 deg. of phase difference at low frequencies) and the negative sign in the phase indicates negative gain (positive elevator deflection for a negative error in glideslope deviation). When the pilot does not use duct lift during tracking, the describing function (α/γ) is a first order lead (20 db/decade and 90 deg. of phase difference at low frequencies) as in Fig. 20. When the pilot does use duct lift, the describing function becomes essentially flat.

A discontinuity in the phase occurs at the 180 degree line, where the curve can exhibit a jump of 360 deg. A jump occurs too in the amplitude because of the jump in the digital numbering system. This discontinuity occurs at the 36 dB line (20* 2048/1134) and must be eliminated for a continuous plot.

Before it was decided to look only at the above two relationships, other combinations have been examined. Although the human operator acts as a multivariable input-output system, no attempt has been made to investigate thoroughly his function. Only an understanding of the control strategy was aimed for in the study of the training. More arguments are given in the discussion of the results.

4.b Methods for deriving the results

The goals set forth for examining the different display instrumentations are:

- the ease of control, which means best performance and least effort

- the optimum landing, which means accurate and smooth touchdowns

The way these goals have been looked at, or the criteria used in the examination are:

- the learning curve of the pilot performance
- the pilot describing function, especially the order of his transfer function and his ability to generate lead in controlling the underdamped system
- the ability of the pilot to track the glideslope in the presence of a wind disturbance
- the consistency in touchdown, described by the mean and the standard deviation of the touchdown range and the touchdown velocity

These criteria have been used to compare the types of instrumentation discussed in Chapter 2.

4.c. Discussion of the Results

1. As expected, the pilot goes through a training period before reaching a steady state level. Unless one has observed that the training period is over, one cannot be sure steady state performance has been achieved. This is especially true since after some time, fatigue is observed. This fatigue was both physical and also emotional since pilots often reached a point where they felt that they could not further improve their performance, and their motivation to work hard

was diminished.

A typical learning curve is shown in Figure 21, which is given for the tracking score alone and also for the combined performance, tracking and touchdown. It turns out that both curves are highly correlated. If the pilot is unable to satisfactorily track the glideslope, it will be impossible for him to obtain a decent landing score, and vice versa. This was the case for types 1 and 2 in the conventional instrumentation of display. This was not the case for the perspective glideslope, however. This will be discussed in a separate section.

2. Observation of the pilot describing function for tracking the glideslope reveals that there are different categories of transfer functions (Fig. 22) for δ_e/e_h :

- gain with time delay
- gain
- first order lead
- second order lead

Inexperienced subjects begin their training by acting as a pure gain. In the case where the glideslope needle has gone off scale, their describing function is a gain plus a time delay. Improvement in their performance brings them to the next category. Pilots with intermediate experience start exhibiting a first order lead in their describing function. As time goes on, they change their gain and after

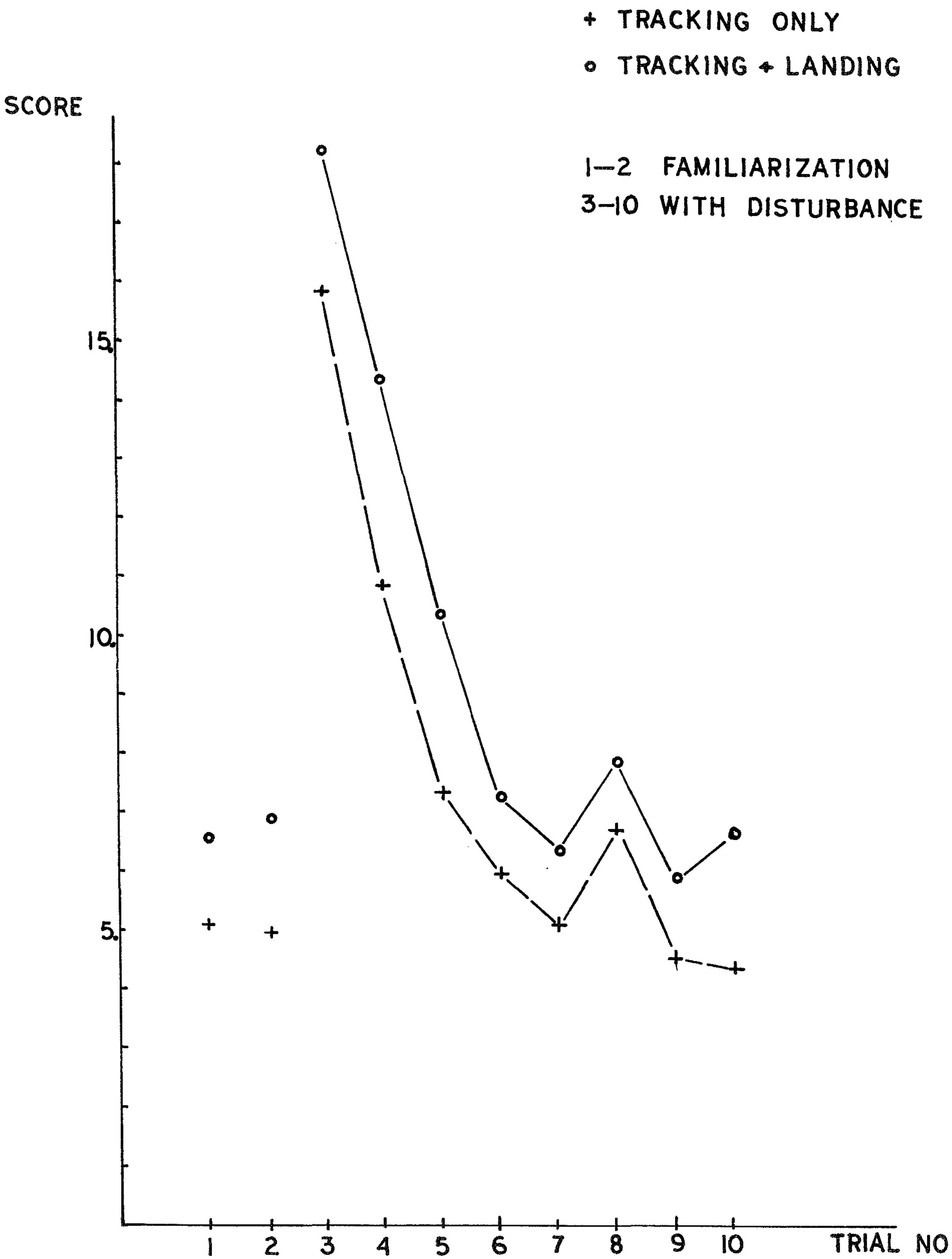


Fig. 21. Learning curve for an experienced pilot, using the conventional instruments.

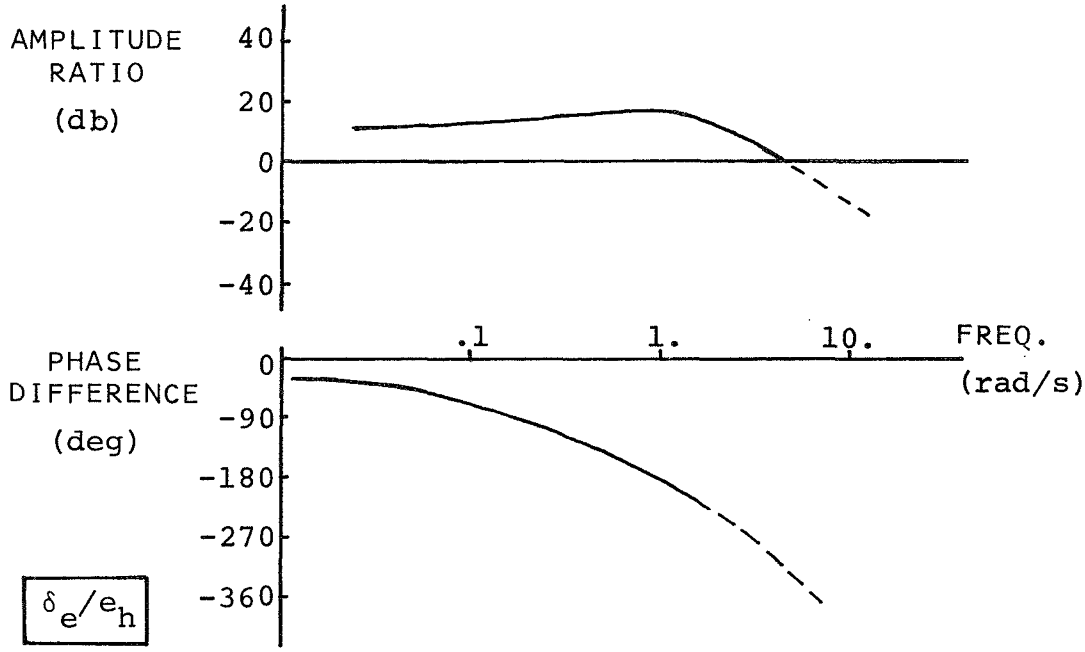


Fig. 22a. Pilot describing function : gain with time delay.
(Case of an inexperienced subject, using the dial instruments).

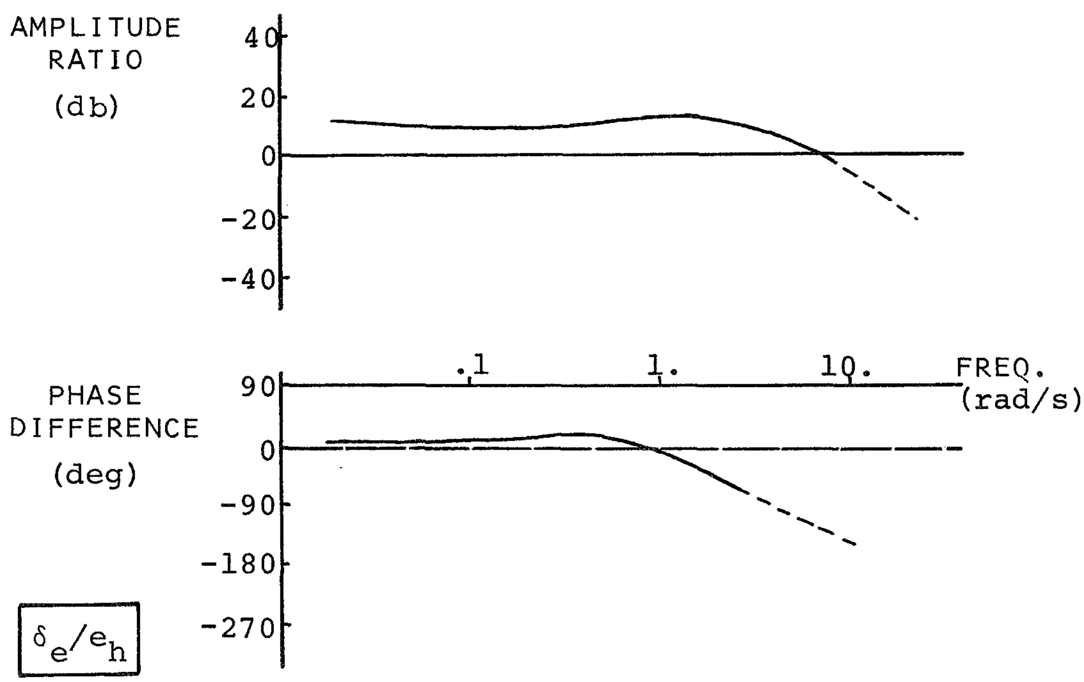


Fig. 22b. Pilot describing function : a simple gain.
(Case of an inexperienced subject, using the dial instruments).

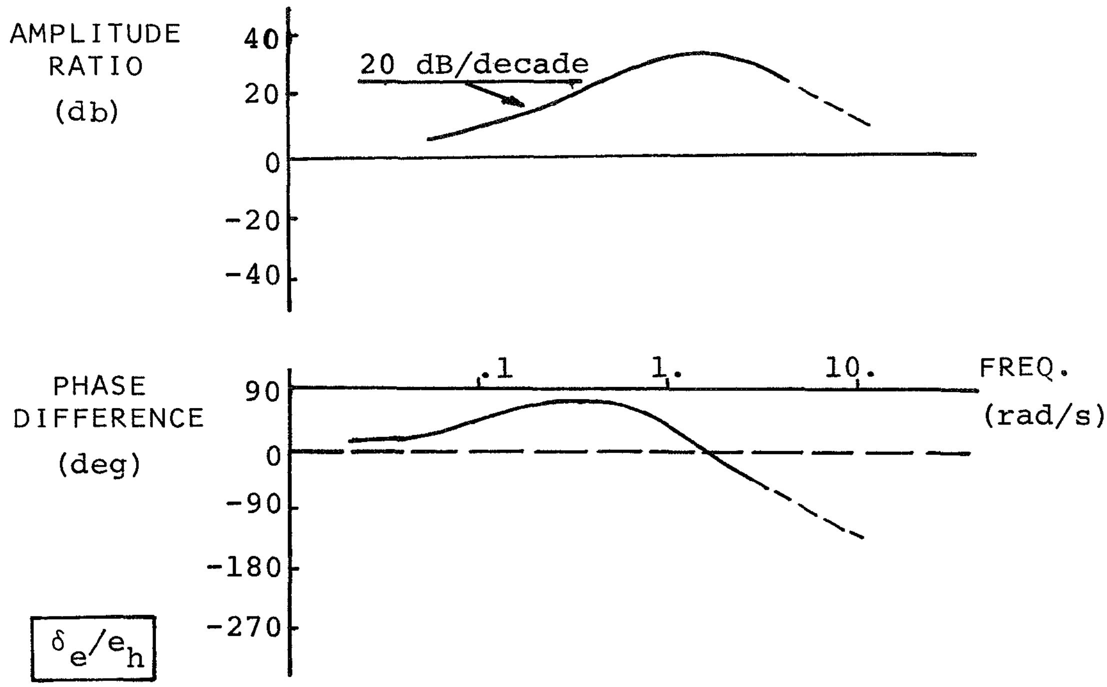


Fig. 22c. Pilot describing function : lead generation.
(Case of a pilot with limited experience, using the dial instruments).

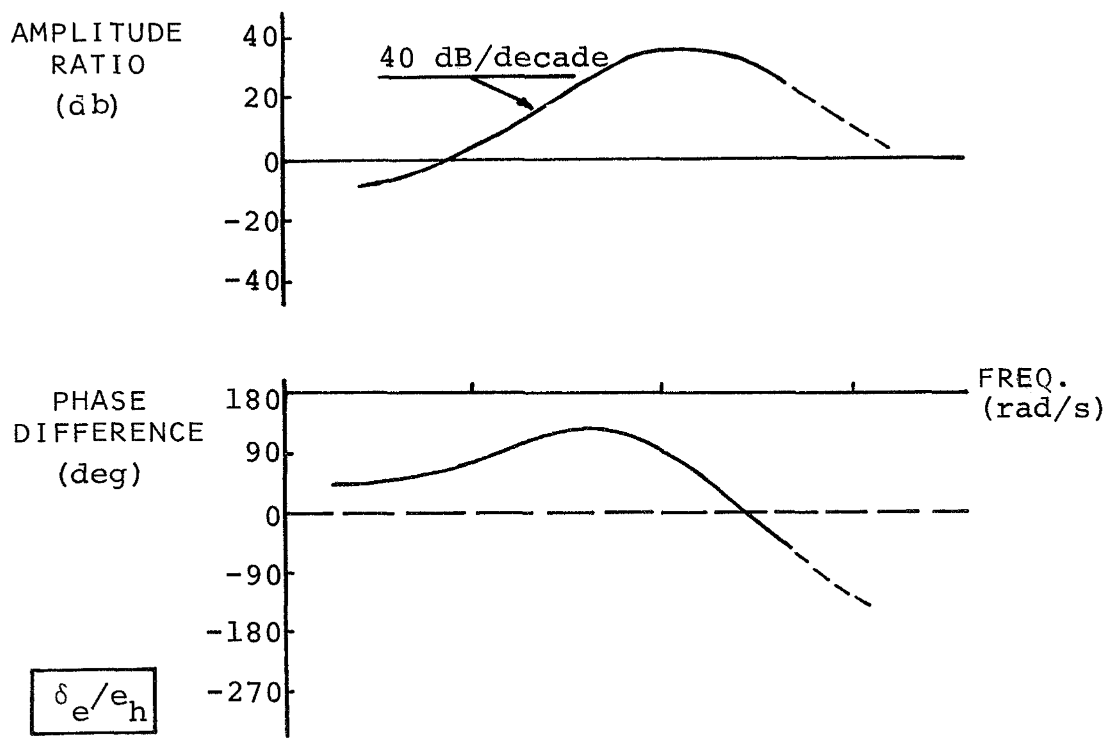


Fig. 22d. Pilot describing function : a second order lead.
(Case of a well-trained pilot, using the dial instruments).

some time, they reach the "third level" of control strategy. The highly skilled pilots exhibit a second order lead. They achieve this by applying a control technique in a pulsatile manner: an elevator control pulse in one direction, followed by a pulse in the opposite direction (Ref. 160).

When applying the wind disturbance it turns out that each class of pilots exhibits one less order of control skill at first depending upon total experience in aircraft. They eventually succeed in controlling the aircraft in the same manner as before the disturbance was applied.

Different techniques were observed depending upon the glideslope. For the steep glideslopes, for example, the experienced pilots behave as a time-varying system(Fig. 23), a combination of first and second order strategies. The pilots from the intermediate group tend to do so, too.

3. Because of the training phase, one cannot put the same weight on the results of each experiment. It is advisable to separate these and to look at the steady state performance. Training and learning time, however, are factors of secondary improtance.

<u>4.d. The results of the experiments</u> are described with the following items :

- mean and standard deviation for touchdown
- mean and standard deviation for touchdown velocity
- mean and standard deviation for tracking ability

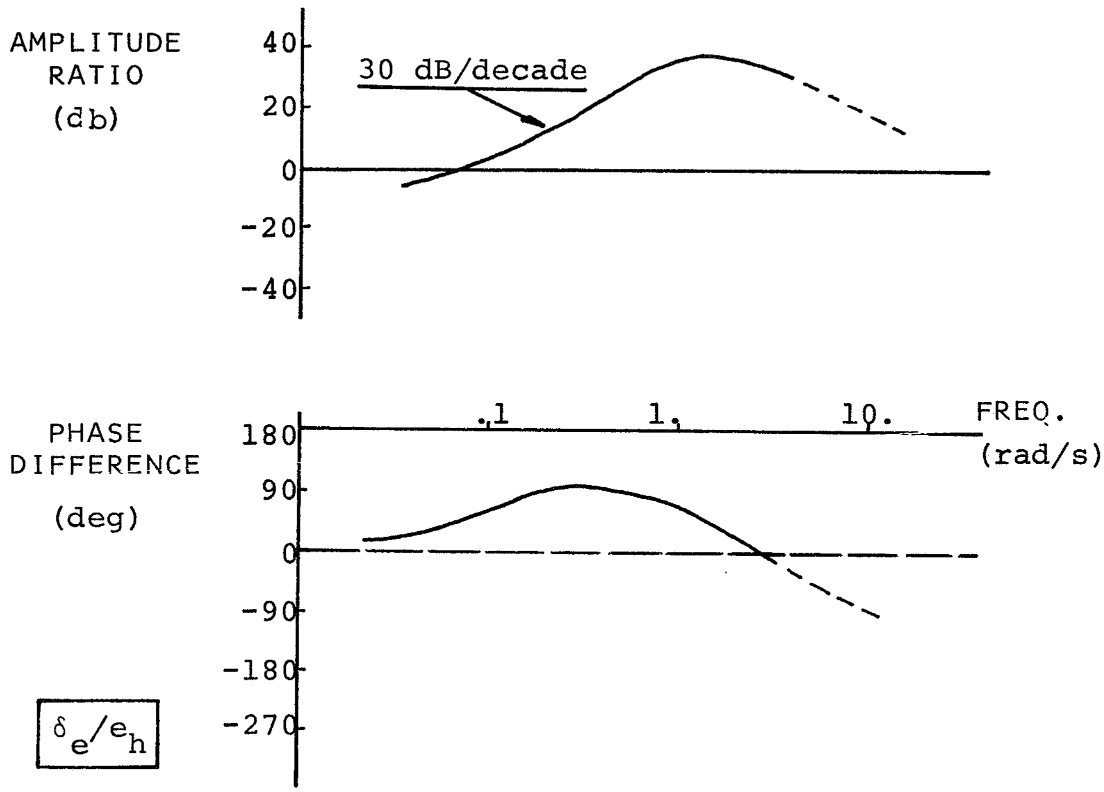


Fig. 23. Pilot describing function showing the pilot as a time-varying element.
(Case of a well-trained pilot, using the dial instruments for the steep glideslope of 17.3°).

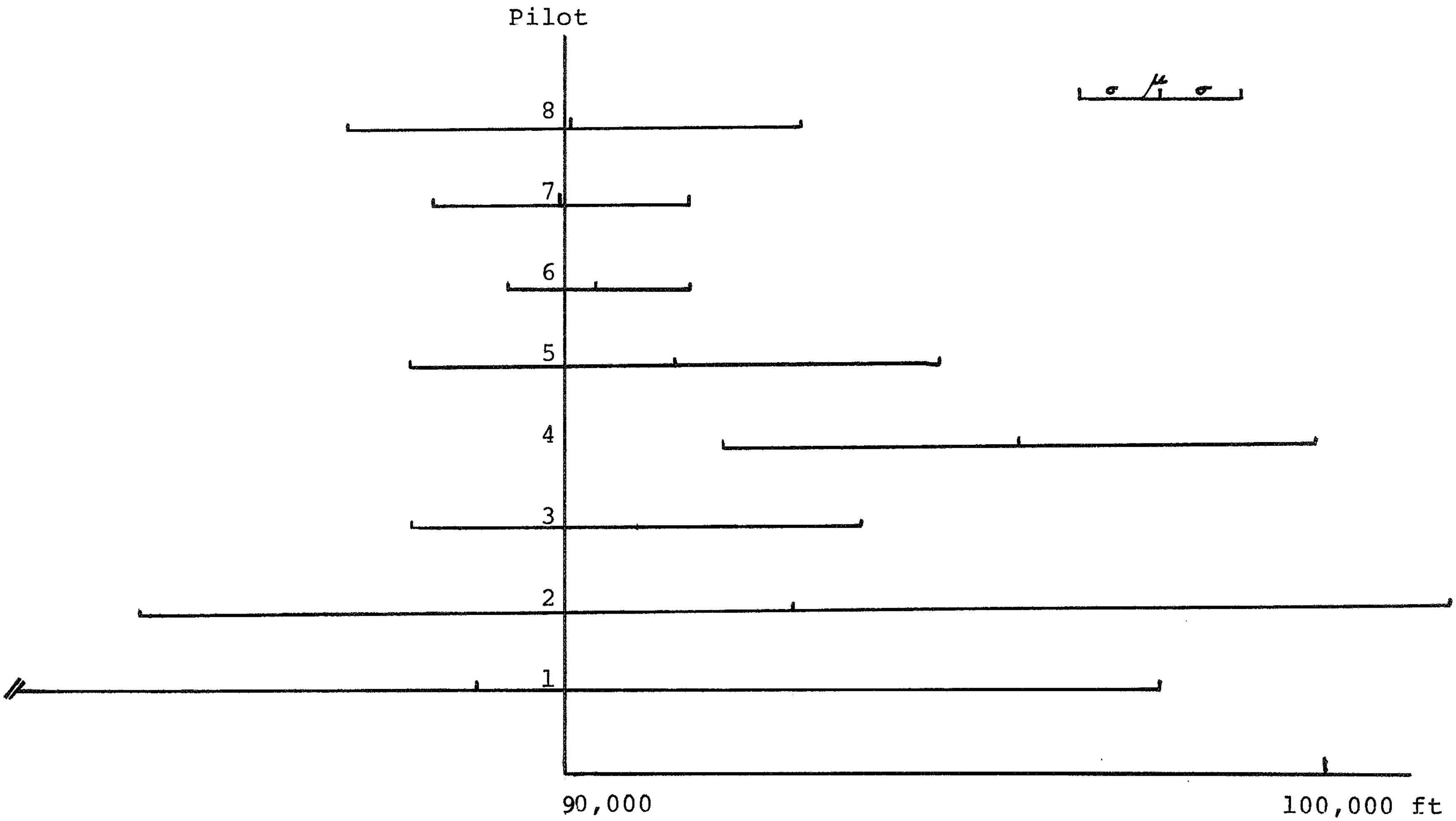


Fig. 24a. Range at touchdown in the case of the dial instruments.

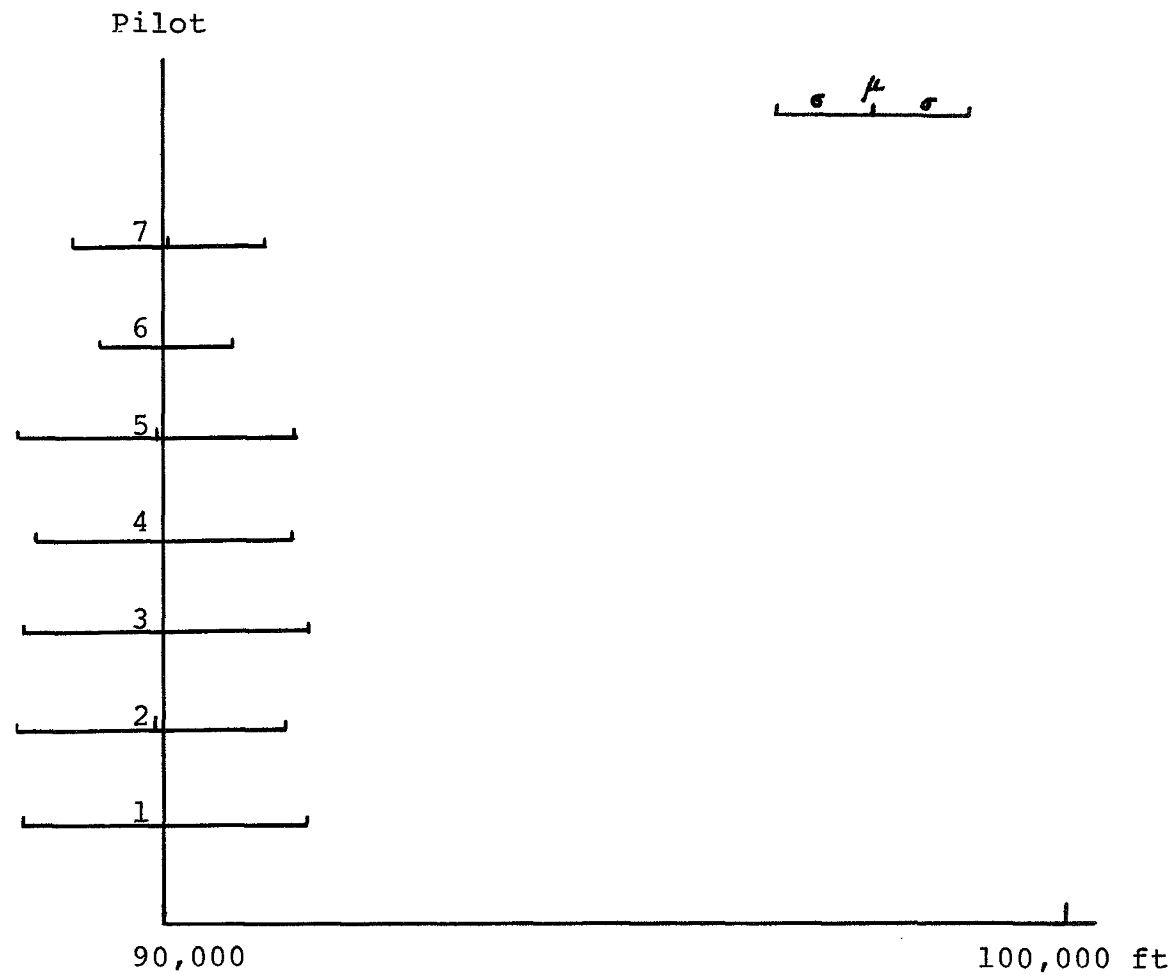


Fig. 24b. Range at touchdown in the case of the perspective display.

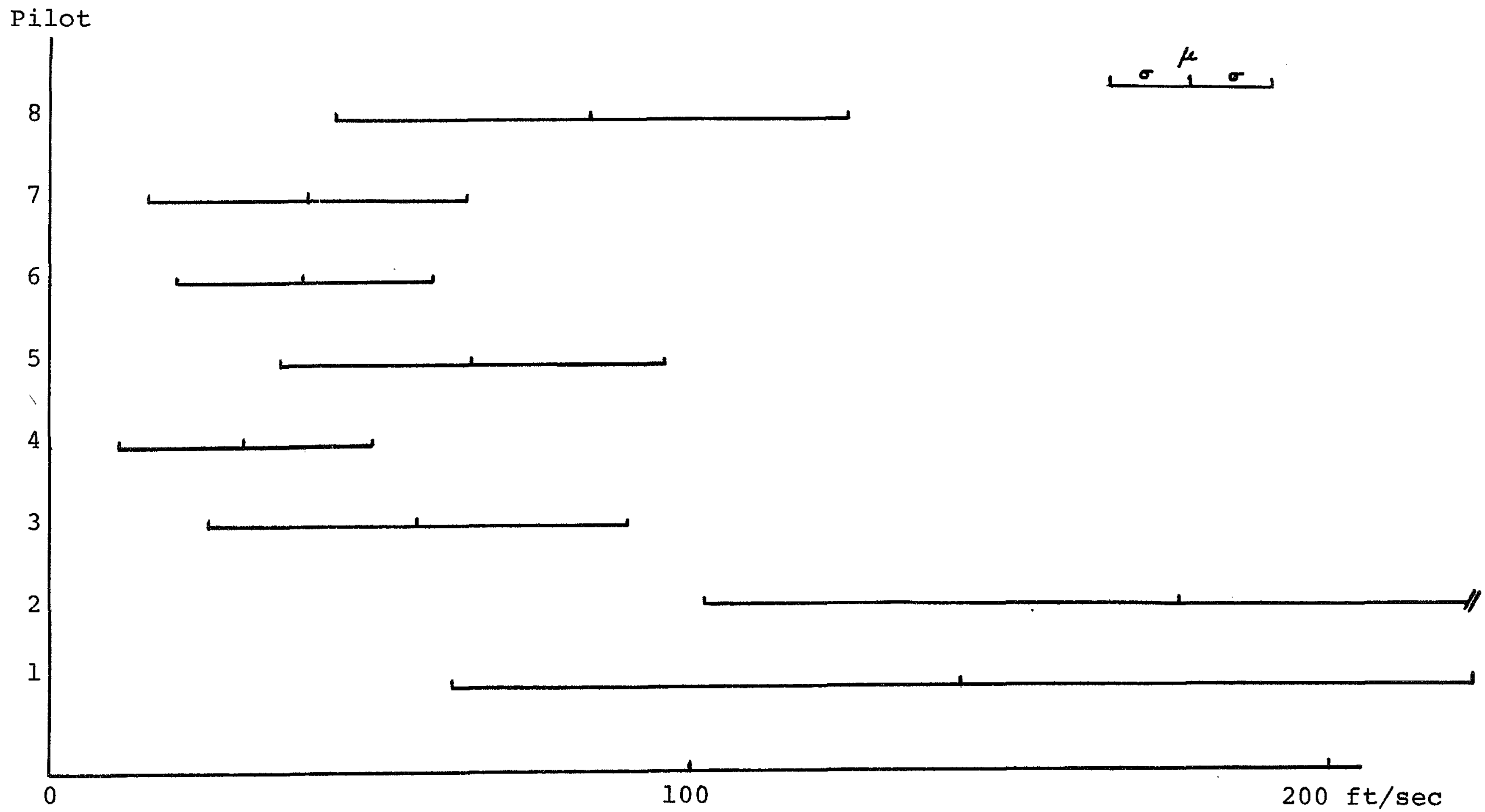


Fig. 25a. Vertical touchdown velocity in the case of the dial instruments.

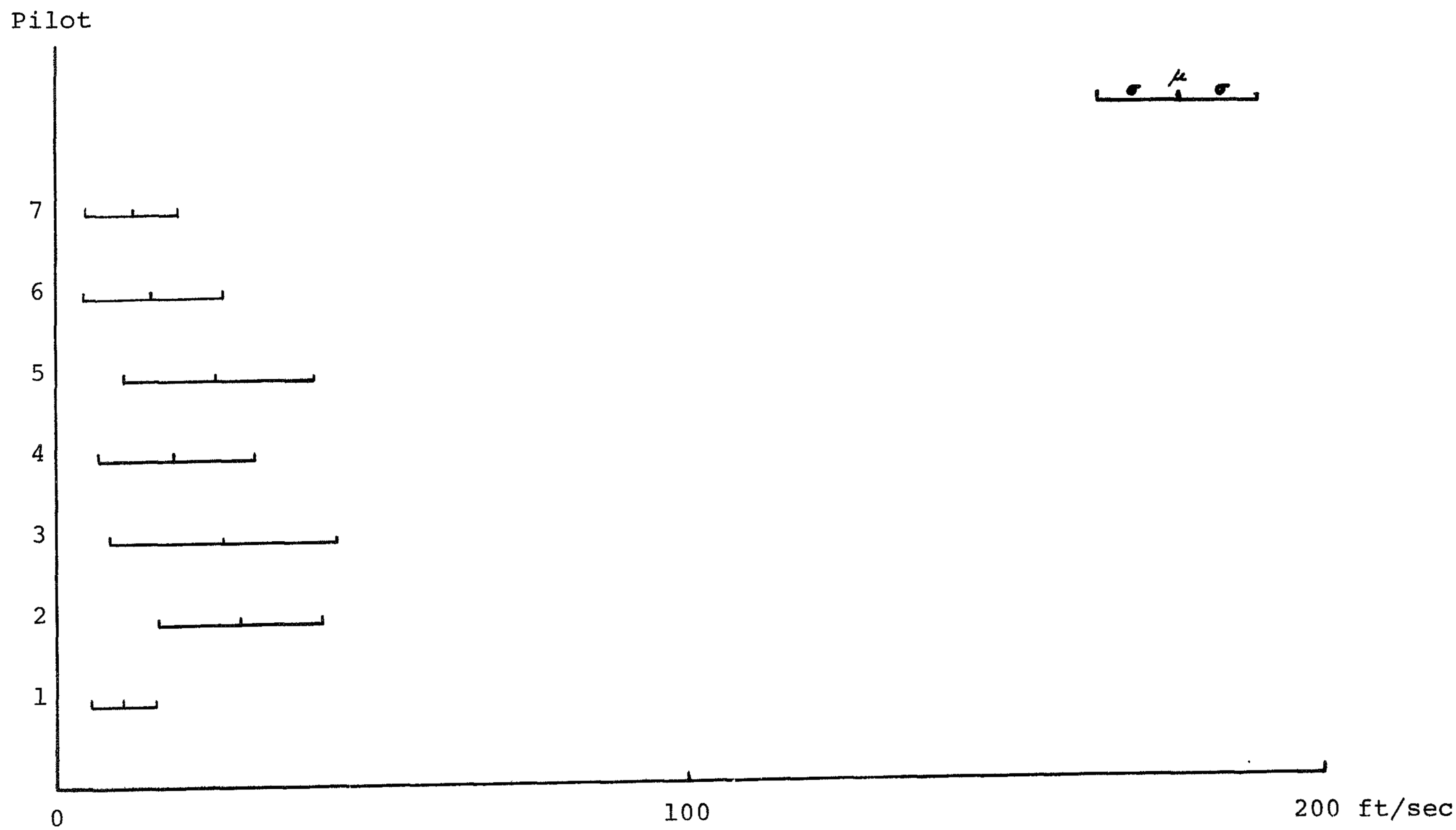


Fig. 25b. Vertical touchdown velocity in the case of the perspective display.

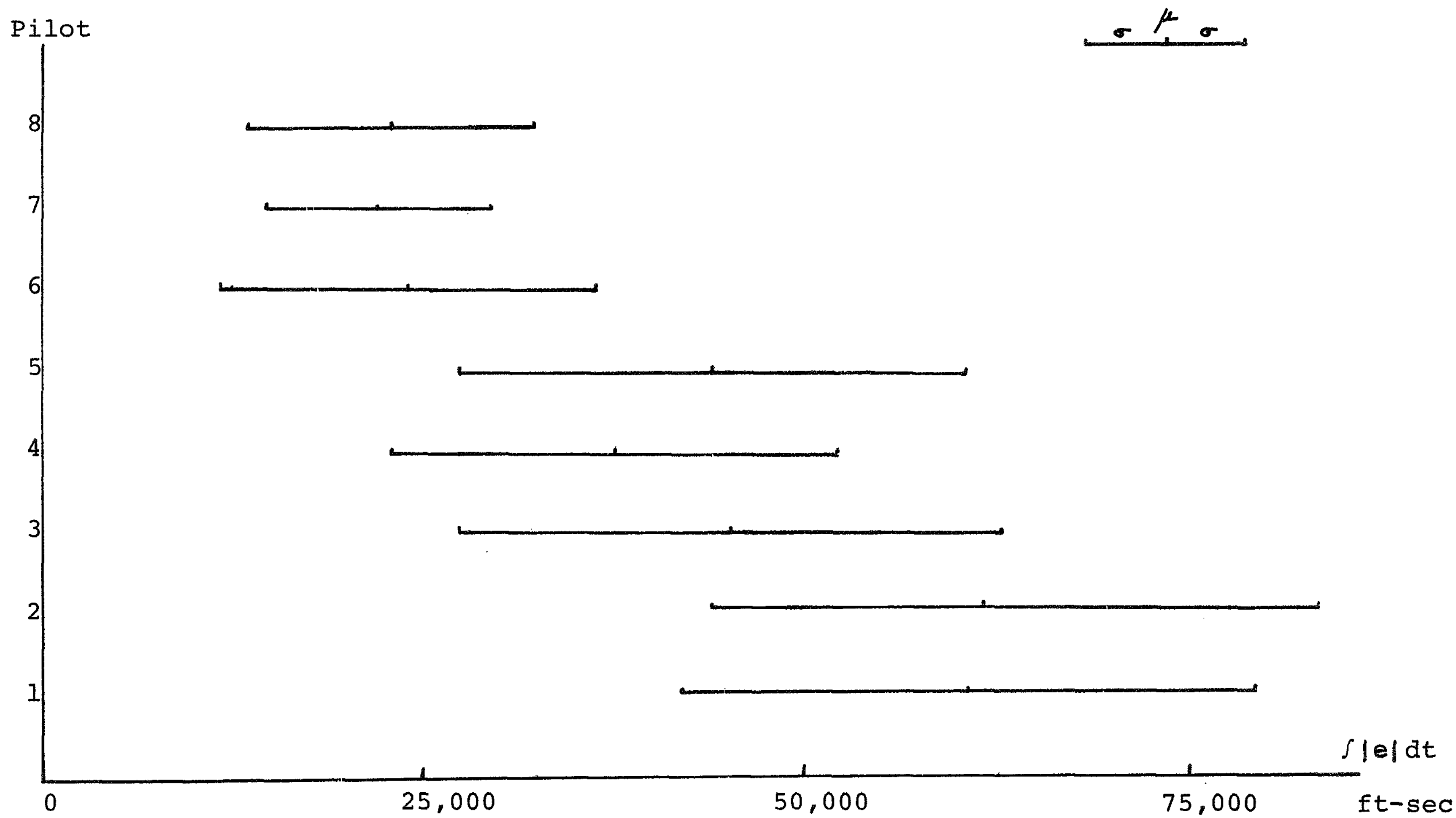


Fig. 26a. Tracking performance in the case of the dial instruments.

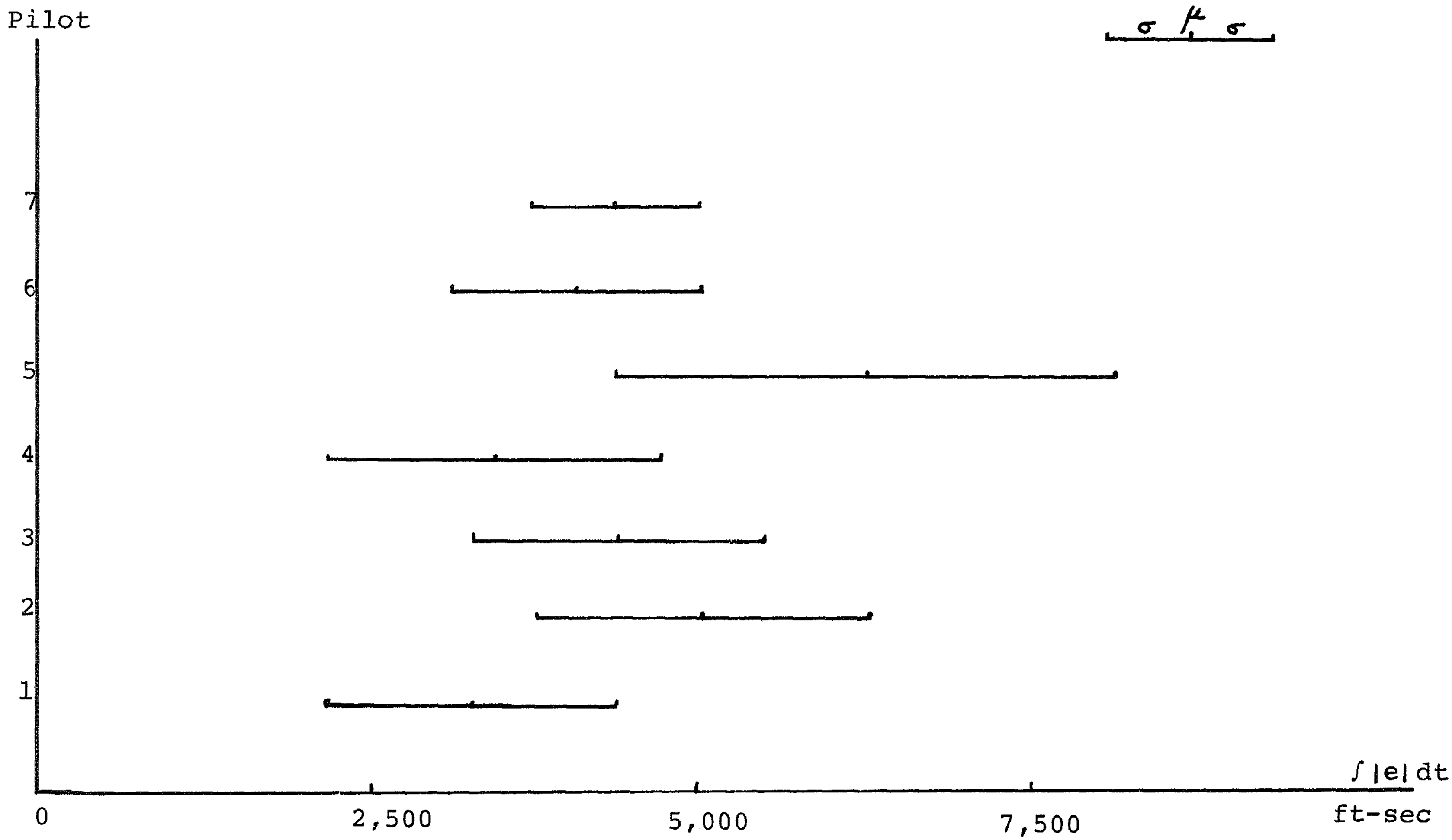


Fig. 26b. Tracking performance in the case of the perspective display.

The results are given for each pilot, for each glideslope condition, and for each arrangement of instruments.

A graphical representation, comparing the above items for each pilot, without and with display is given in Figures 24a and b, 25a and b, and 26a and b, respectively.

Examination of the records shows that there is a distinct difference in the performance between the simulated flights with the display and those with the dial instruments. Figure 27bshows the records of the flight path of an inexperienced subject using the perspective glideslope display. This compares with Figure 27a,showing the record of an experienced pilot using the dial instruments. Note that once the perspective display has been explained to the inexperienced pilot, he performs better than his more experienced counterpart using the dials above. Figure 28 shows the learning curve of an inexperienced subject using the perspective display and it must be noted that the curve is essentially flat. This must be confirmed with Figure 21 which is for an experienced pilot. Note too the order of magnitude difference between the performance score factors. (Their definition is given in Volume 2, Section 3.) The improvement in performance and the ease of control is as striking and as remarkable as the improvement in the improved display in Ref. 157.

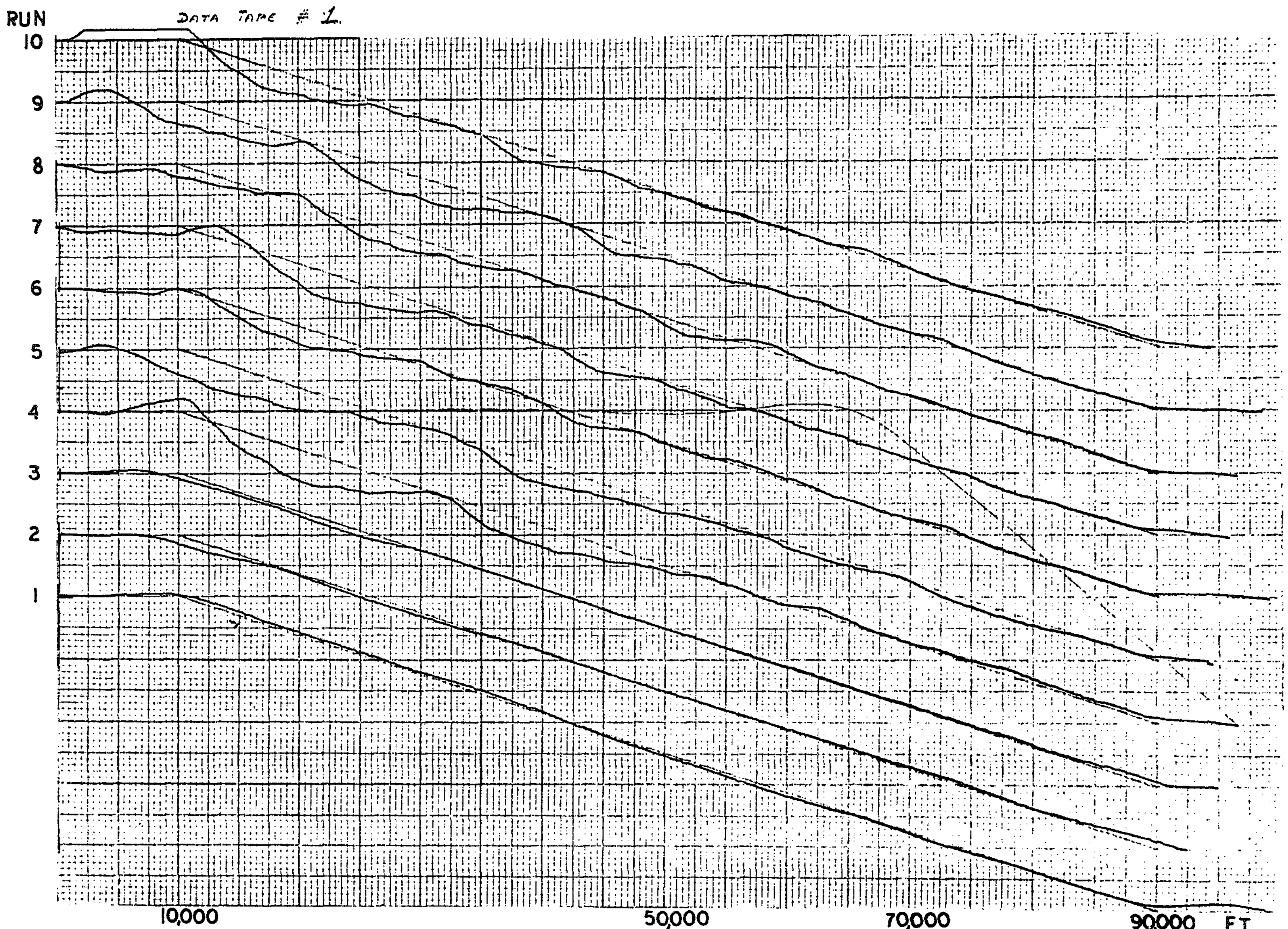


Fig.27a.Flight path record of well-trained pilot, using dial instruments.

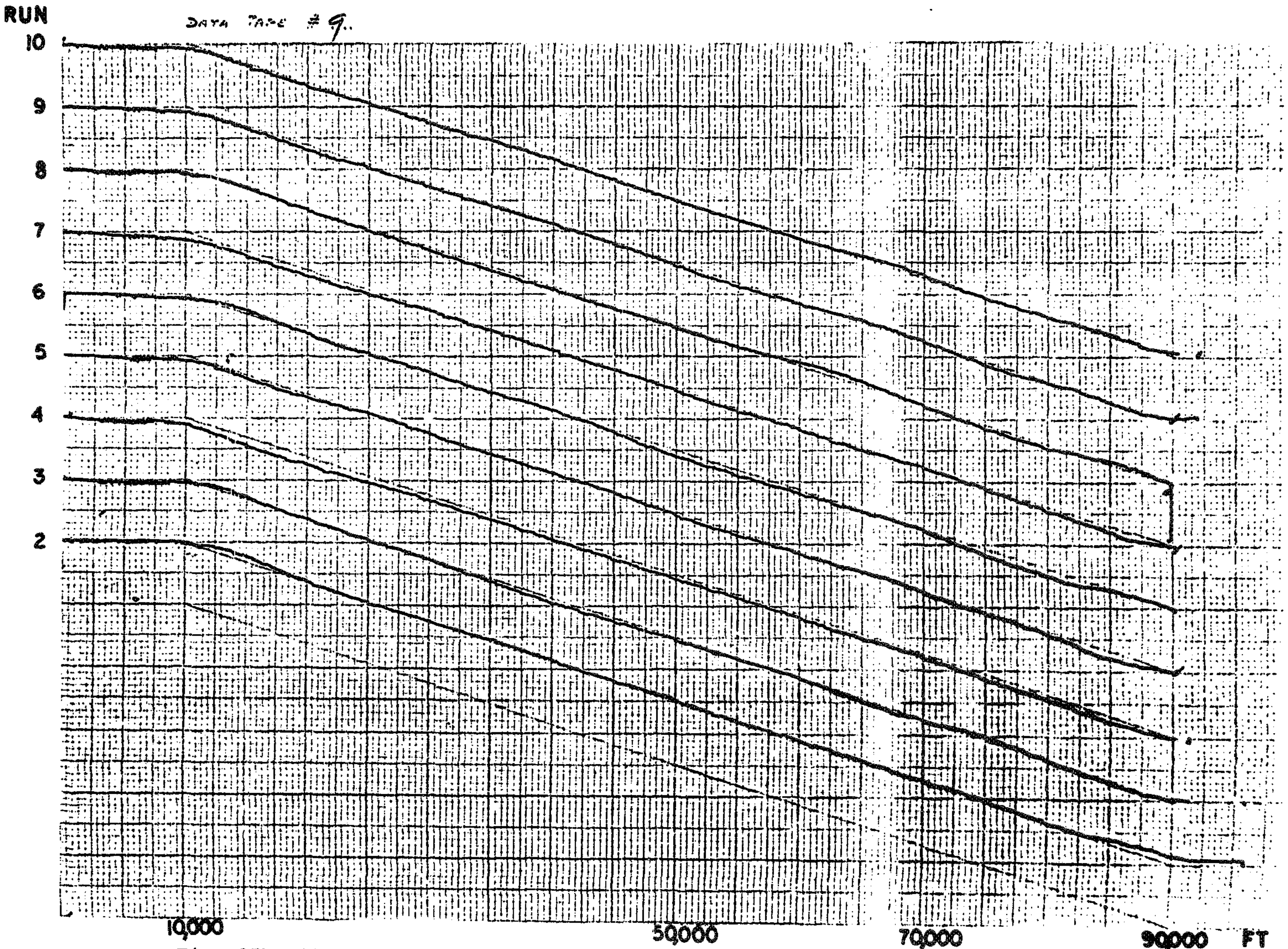


Fig. 27b.Flight path record of inexperienced subject, using perspective display.

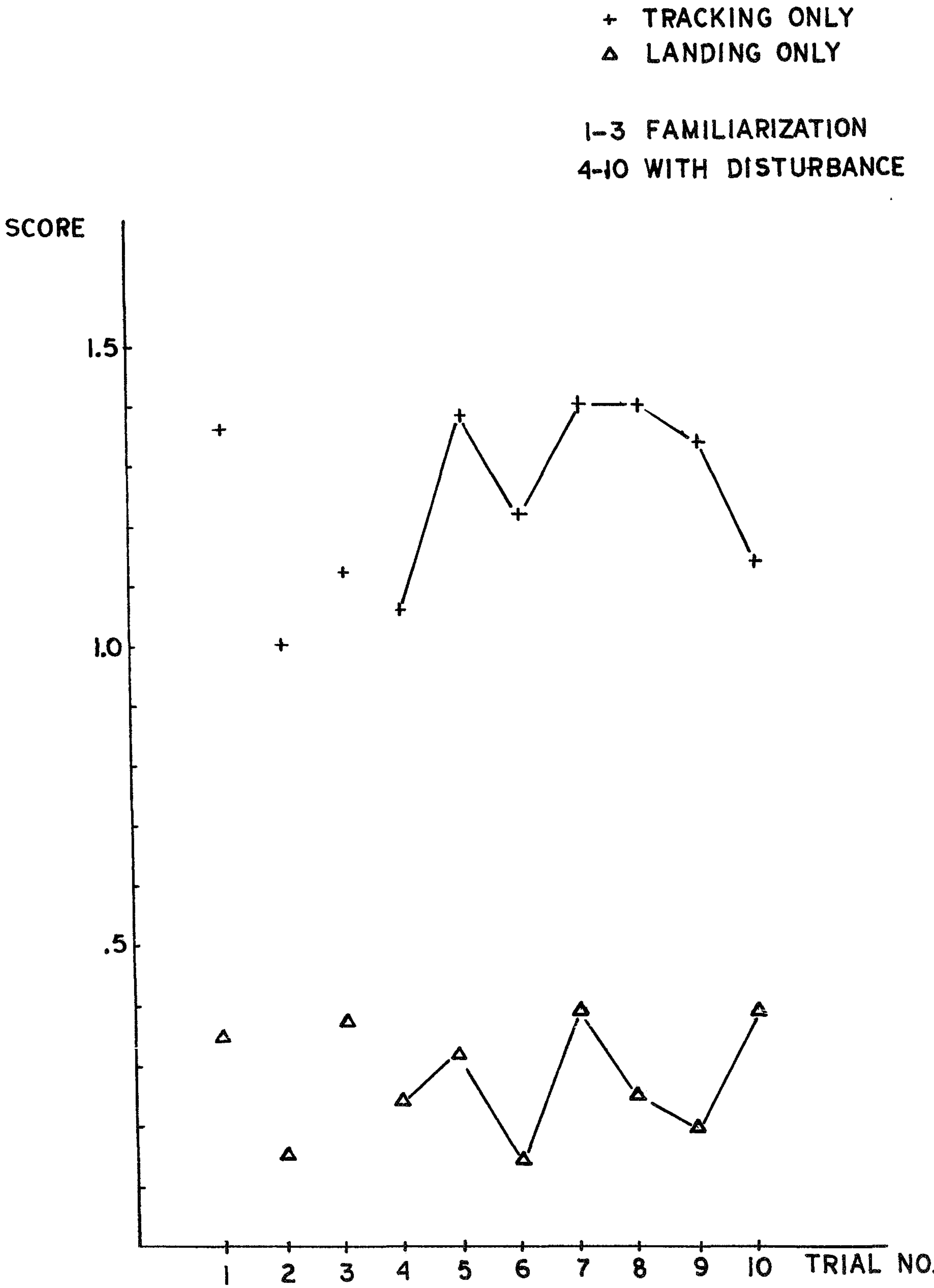


Fig. 28. Learning curve for an inexperienced pilot, using the perspective glideslope display.

The results, presented in Figures 24a and 25a especially, are quite high, compared to numbers in real life. Indeed touchdown errors exceeding 1000 ft and vertical velocities at touchdown larger than 10 ft/sec (the maximum allowable on an aircraft carrier) are somewhat ridiculous. This indicates the lack of loop closure and no damping when using the conventional instruments in an aircraft without stability augmentation. However the perspective display did permit sufficient damping through inner loop closure.

The differences of performance in these two conditions were sharply underlined by the difficulty of the task :

1. the aircraft has been simulated without the artificial stability augmentation.
2. tracking a glideslope much larger than the nominal 3° glideslope for conventional aircraft is difficult. The glideslopes under investigation went up to 17.3°
3. a wind disturbance was applied in a vertical direction to make the aircraft drift away from the glideslope. The maximum amplitude was 50 ft/sec at the cruise altitude, but was proportional to altitude.
4. the control of a V/STOL aircraft is not a task which one can learn easily because more than one method can be optimum. This has been observed in the different stragtegies of the pilots.
5. the control task in landing this aircraft consists of controlling simultaneously three variables : pitch attitude, power setting and thrust direction. This task

is considerably easier while landing a conventional aircraft. Once the power setting is done, mainly one variable, pitch attitude has to be controlled.

When the artificial stabilization was reinstated, the simulated aircraft could be flown well enough for the glide-slope of 3°. However the above mentioned items 2, 4 and 5 are proper to V/STOL aircraft. Therefore conventional instruments alone are insufficient for the task.

This is illustrated better by the results (tracking, touchdown and vertical velocity at touchdown) for glideslopes of different steepness (Fig. 29). A very steep glideslope (32°) has been added to the plot. The data, for experienced pilots only, indicates that the range at touchdown becomes more accurate for steeper glideslopes. This is due to the reduction of forward speed in order to stay on the glideslope, while maintaining a reasonable sink rate. However this operation requires a lot of fuel and requires some piloting skill to handle the duct lift. The touchdown velocity is more difficult to handle when the glideslope increases. The values (gotten for the perspective display) are still acceptable, but are at the limit for the very steep glideslope. This suggests the use of a sensitive read-out of sink rate near touchdown.

A comparison with the pilot opinion and the Cooper rating is given in Chapter 5.

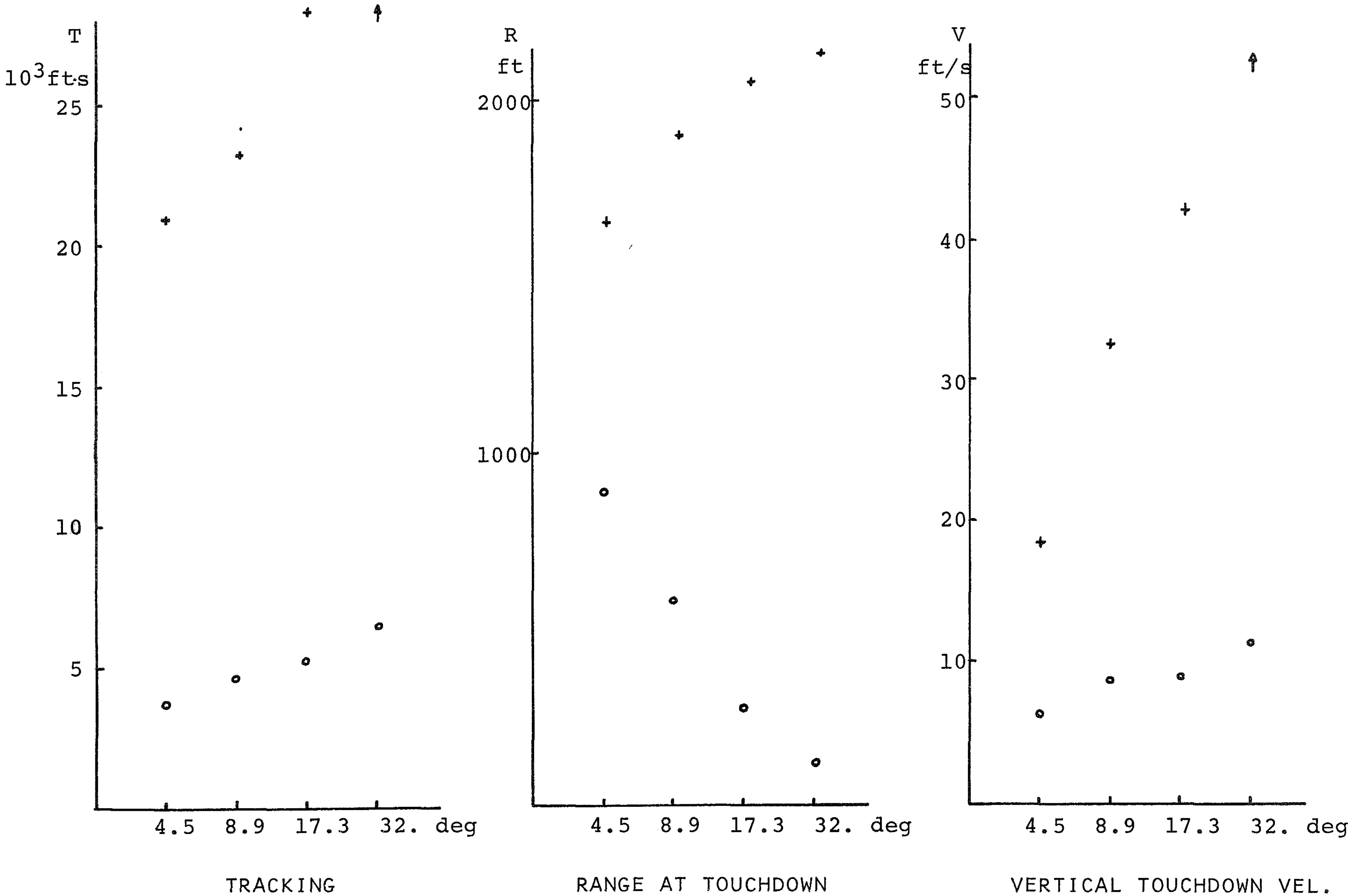


Fig. 29. Comparison of pilot performance for different glideslopes.
(+ conventional dial instruments ; ∘ perspective display)

4.e. Discussion of the Data

From the tables and graphs one can conclude that the display creates a significant improvement in performance.

1. The consistency in touchdown is shown in that the mean is close to 90,000 ft., the desired touchdown point. The variance shows that with the display all three classes of pilots do equally well.

2. The consistency in touchdown vertical velocity is shown in the mean and variance. Quite often the pilots were able to touch down with say 2 or 3 ft/sec and only one bad result was enough to hurt their scores significantly.

3. Tracking the glideslope has become very easy with the display. The pilots all reported that the display was very sensitive to elevator control and they did not realize that this was also the case with the dial instruments only. This is probably the most striking proof that lead generation is much easier with the display.

Difficulties, however, in measuring this quantitatively are many:

- the system dynamics are non-linear
- the pilot behaves as a time-varying system
- the system is multimodal
- the power of the input disturbance could not be made high enough

Typical runs in which the pilot relied on conventional dials show that a large glideslope deviation accumulated with the display off, but was nulled in a dead beat fashion from the moment the display was turned on.

4. The learning curve with the display becomes essentially flat (Fig. 28), i.e. no improvement is observed between the first run, when the pilot fully understands the display, and the last run. Moreover, fatigue is almost unnoticable. One pilot, for instance, did all three experiments in a row, for three consecutive hours. He was rechecked at a later date on the last run of the series , and no significant difference from his earlier performance was observed.

5. The present figures are somewhat large compared to actual flight data. The large variance for touchdown range and vertical touchdown velocity, in the case of the dial instruments, is due to a lack of stability augmentation. These values are more reasonable in the case of the perspective display. However, the relatively large mean for the vertical touchdown velocity is due to the resolution and computer noise. From Table 1 in Volume 2, one derives that 1 bit represents 0.625 ft/sec and the A/D convector sometimes is in error by 5_8.

4.f. The Effect of Training

All the pilots went through the series as indicated in Chapter 2: first no display, and then the display. It can be argued that they all learned well on the more difficult task. Therefore, they should do even better in the case where the display is used. For that reason, three pilots were examined, first with the display, then without. The difference in performance is even more remarkable. With the display they start pretty well, and learning is insignificant. However, without the display, they have some experience on how to handle the control. At first they apply the same technique and the performance, although no longer as good, is much better than what it becomes later on. They lose gradually all that they have learned and get confused, they say. The work is much harder too and at the end of the experiment, their performance can hardly be compared to that of the beginning. A comparison of the data of these subjects is given in the Figure 30.

4.g. Discussion of the Qualities of the Perspective Display

The primary purpose of the display, as given in Figure 15 is to accomplish the following mission: to steer a relatively unstable aircraft (as a V/STOL aircraft) from cruise altitude rapidly (along a steep glideslope) to a hover condition (relatively low groundspeed) nearby the landing site and to land smoothly and safely under low to zero-zero visibility conditions.

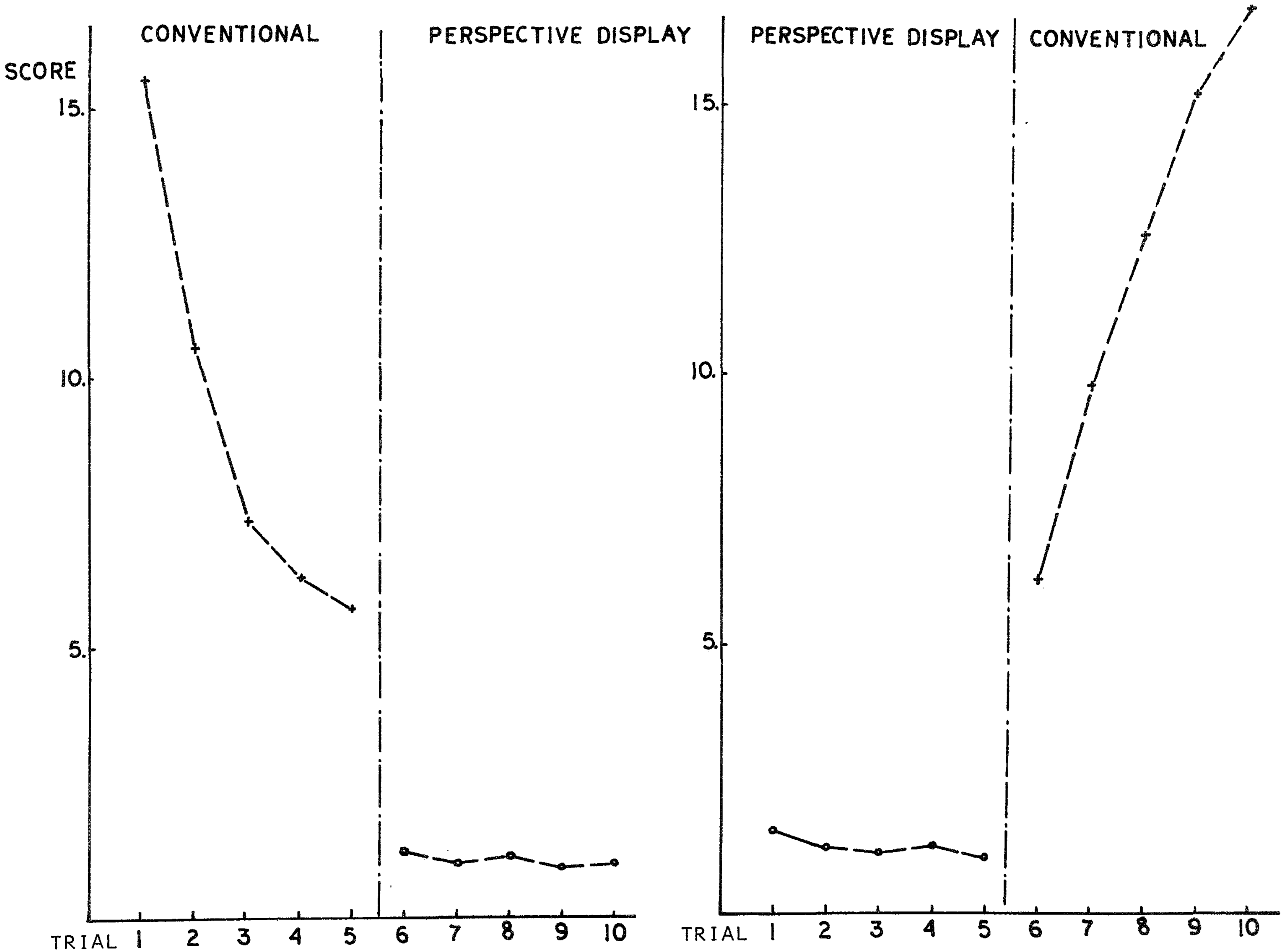


Fig. 30. Effect of the order of the instruments on the tracking performance.

The design and properties of the proposed perspective display will now be discussed.

1. The display is of the <u>contact analog type</u> and thus allows coordinated maneuvers to be performed much more easily than with the conventional instruments. The changes of variables can be made much more rapidly, without taking risks, than a stepped-up approach, in which a cyclic scan pattern from horizon indicator via airspeed indicator to position indicator involves more time, more skill, more understanding.

2. At all times the <u>"outside" world picture</u> is visually compelling, and the pilot never has to integrate the situation by reading several dials, a procedure which is subject to hazards. This "real world" picture will tend to prevent the pilot from becoming confused, especially in vehicles where the motion experienced by the pilot is not similar to that of the aircraft itself as a whole. In emergency situations where the effects of a hazard would trigger several dials to change rapidly and seemingly inconsistently, the display will present the situation conspicuously in an easy to understand fashion.

3. Rather than having a status-information of all available parameters, the pilot is able to <u>derive the rates of change</u> of those parameters. He will be able to anticipate this motion and he can act with the controls to make

his airplane respond with a dead beat response. This type of response can only be gotten with a quickened display. However, it has the disadvantage that one does not know the state of the variable and secondly one cannot respond in any other fashion than imposed by the quickening gains. The display has neither of these disadvantages. A scanning pattern created by dial displays makes the pilot lose the rate of change of the observed quantity as soon as he takes his eyes off one instrument to go to the next one.

4. For improved performance in a compensatory tracking task, one can successfully apply non-linear gain. This concept is employed in the glideslope display due to the very nature of perspective. It is used in two different ways: first to allow easier tracking of the glideslope, and second to allow a smooth touchdown. At the desired glideslope, the perspective lines move rapidly about the horizontal reference line and allow observation of offset errors of less than 10 feet, at altitudes of 20,000 feet! Away from the glideslope, the sensitivity of the error indication decreases rapidly. An identical sensitivity range is obtained about the ground plane, where the only interesting region is above the ground level. Similar sensitivities are obtained where altitudes of less than 2 feet can be discriminated. The sensitivity variation behaves as an "arc tangent" law with maximum sensitivity around the horizontal reference line. This maximum can be changed

arbitrarily and can be set much higher at the ground level than at the glideslope. This setting depends upon the screen size and the roadway width (as indicated in chapter 3), and it remains unchanged during the landing approach.

Controlling a relatively highly-underdamped plant happens quite often in the presence of sustained oscillations. Improvement in the control can be gotten by applying a command input signal, which one is aiming for. In a similar manner, the display can be flown such that the pilot sees where to go. He puts the point, he is aiming for, in the center of the screen, his airplane reference. The manner to achieve his goal is entirely free and is left up to the pilot, and he himself has the possibility of adaptation.

CHAPTER 5

THE THREE-DIMENSIONAL SIMULATION

5.a Generalities

The equipment used for the experiment was quite limited in size. The digital computer has only a 4K memory while the analog computer has only 20 integrators. With these limitations, it was quite a challenge to set up this experiment. To indicate some of the extremes reached with the "available" equipment, it is of interest to mention the following:

a. The zeroth page normally has 120_{10} locations available for direct addressing from anywhere in core. With careful usage of double and even triple definition of variables, this page has been expanded to be able to contain 200_{10} variables.

b. Not a single location in memory is "left over." The permanent loader page also has been used as a data buffer, and core has been expanded by swaping programs between the two major cycles in the experiment.

c. The experiment program has been running with an efficiency of the processor time equal to 280% normal processing time, using the multiple interrupt feature.

d. The number of available DA channels is eight. It was necessray to set up a logic controlled by software to multiplex these channels and to expand them to an equivalent of twelve DA channels.

e. Special subroutines for real-time operation had to be written to make the experiment possible. The time required for their operation is on the average about twenty times faster than commercially available routines. In addition, the routines are more compact.

Besides these "expansions" it was necessary to carefully consider the program and information flow because of the limited AD and DA channels. For this reason, quite a number of variables were derived on the analog machine to provide the necessary signals for the instruments. It was possible to have a good simulation for all four types of instruments in the planar case with three degrees of freedom (longitudinal motion). However, it was impossible to get a realistic set-up for the three-dimensional case with six degrees of freedom including lateral besides longitudinal dynamics.

Nevertheless, a demonstration had been set up with a crude approximation to the six degrees of freedom : the longitudinal dynamics are computed digitally, using the same non-linear equations of motion ; the lateral dynamics are computed with the analog. This demonstration allowed a study of the display in more difficult-to-interpret situations. Pilot opinion was used for evaluation in this part.

5.b. The three-dimensional simulation.

1. It has been shown in the previous chapter, that the control of a V/STOL aircraft with the perspective display is a relatively easy task. Without confusion it is possible to derive the pitch attitude, the altitude error and the position along the glidepath. It is also possible to perform the landing task with a high degree of accuracy, i.e. the display allows for a quantitative read-out.

Motion in a three-dimensional space with six degrees of freedom however calls for an instrumentation, which is capable of indicating attitude (yaw, pitch and roll) as well as position (left or right with respect to the localizer, too high or too low with respect to the glideslope, and the position along the glidepath).

Although it has been shown (50) that the control of the lateral dynamics of the aircraft do not present any problem in automatic control, the main purpose of the three-dimensional simulation therefore is to show that it is possible to derive each of the above mentioned state variables without confusion.

2. The display program is left unmodified, since it has been written for six degrees of freedom motion. The simulation of the aircraft dynamics have been divided into two groups, and have been computed separately. Two more controls have been added (Fig. 5) : aileron control and rudder control. The resulting attitude changes, roll angle and heading angle are also sampled by the display program.

5.c. Display Interpretation.

In order to understand the display, selected views along the glidepath are shown, using display scheme one (Fig. 31) and display scheme two (Fig. 32). At first no roll is applied, and only a heading change is illustrated. Then, for the same positions and heading conditions, the appropriate roll is included, which makes the airplane follow the illustrated path. This series of views is shown in Fig. 33 and is derived from Fig. 32.

Figure 31 shows display scheme one, which does not have the extended ground lines. In position 1, the nose of the airplane is pointed towards the top of the left distance pole set at 10,000 ft. The second case shows the aircraft aimed at the same pole, but also at the right pole placed at 70,000 ft. The airplane is on the glideslope, with a pitch angle, slightly larger than the glide path angle. In position 3, the airplane is aimed more to the right of the same pole. In position 4, the asymmetry in the picture shows that the airplane is closer to the right, but with a heading parallel to the runway centerline. View 5 shows the aircraft lined up with the runway, but this is not evident from the picture.

Because of this inconvenience and also because of the shortcoming of visual information derived from distant points, display scheme two has been introduced earlier and has been investigated. Figure 32 shows the aircraft in the same selected positions as in Figure 31. This time however, the aircraft's position with respect to the localizer is better

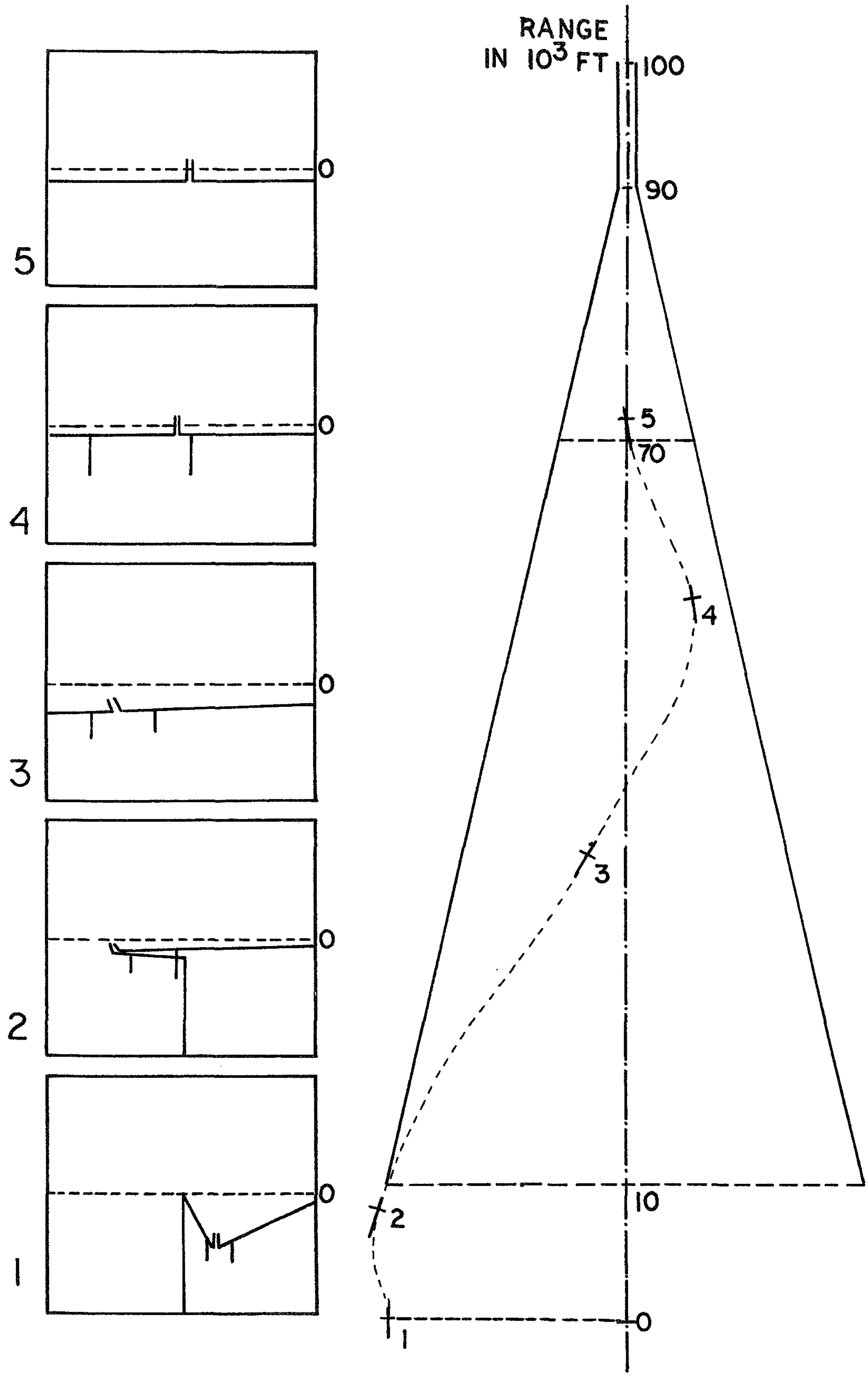


Fig. 31. The perspective display scheme one, illustrating a heading change only.

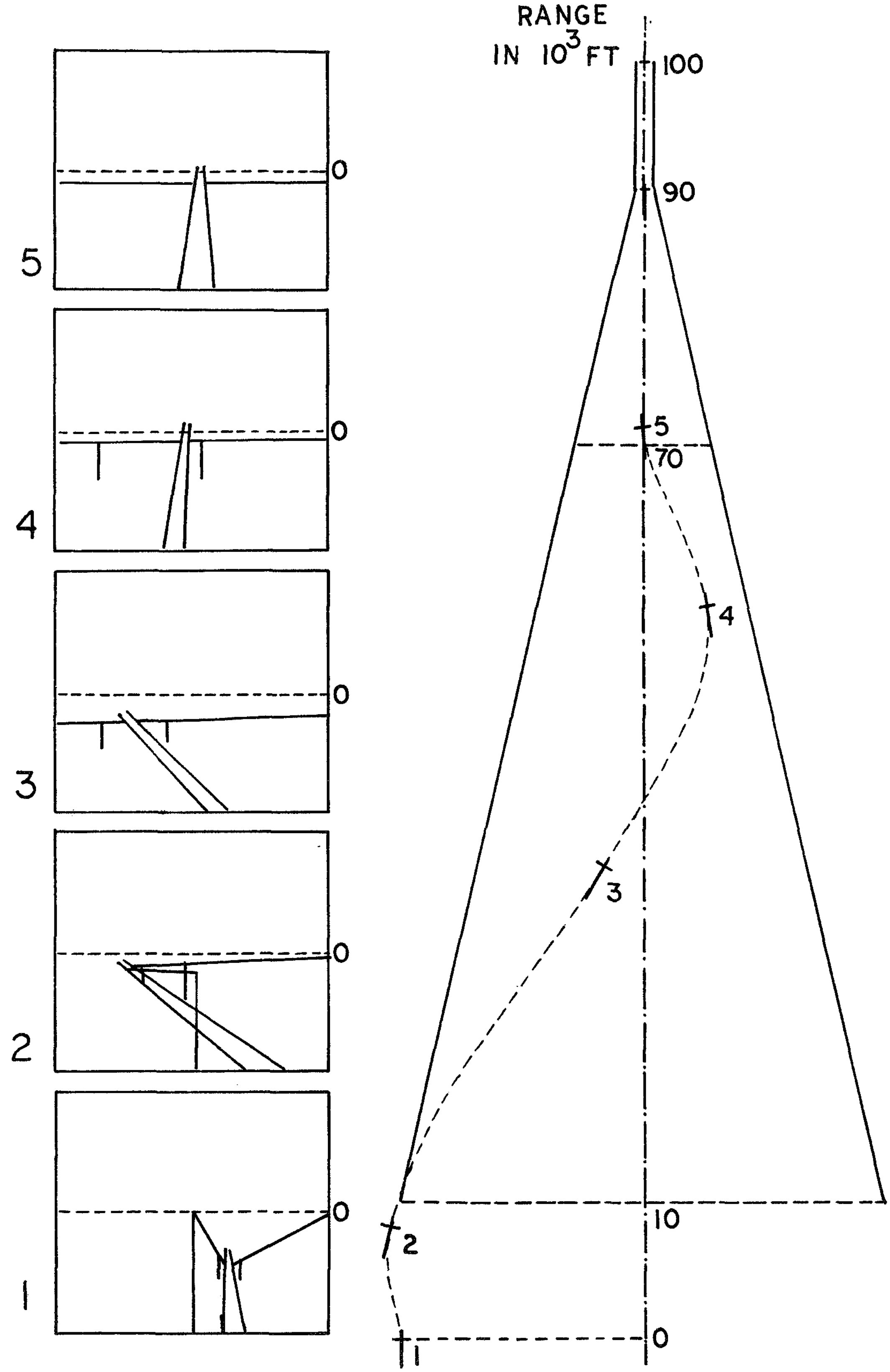


Fig.32. The perspective display scheme two,
illustrating a heading change only.

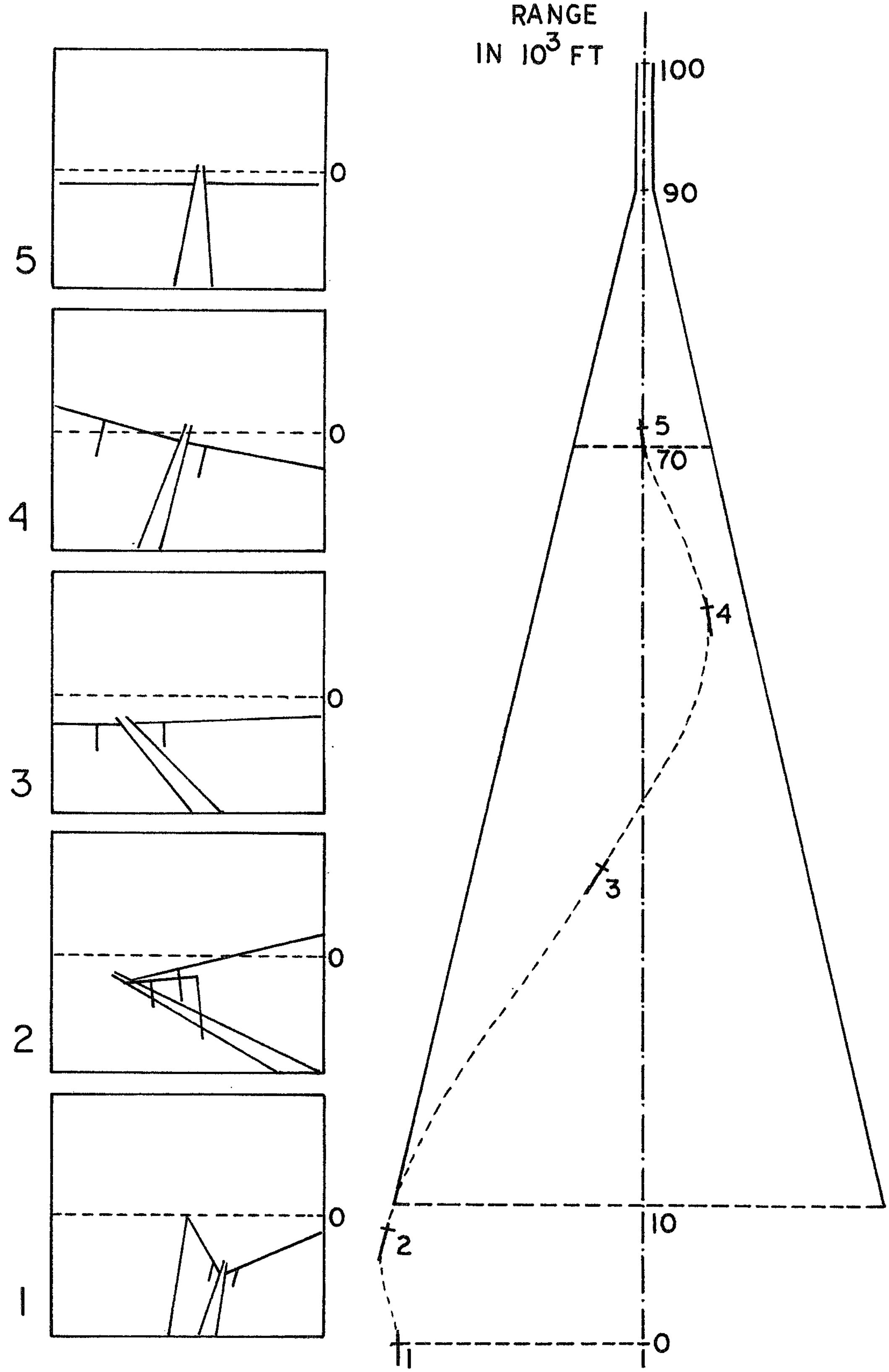


Fig. 33. The perspective display scheme two, illustrating heading and roll changes.

determined. The far end of these extended groundlines indicates the heading, while their location at the edge of the screen is an indication of the position with respect to the localizer. This principle is the same as the pitch information derived from the glideslope lines. For the same reason, a dead beat response while nulling glidepath errors can easily be achieved, as shown in position 5.

Where Figure 32 indicates the effect of a heading change, Figure 33 illustrates the effect of roll added to the conditions existing in Figure 32. Frames 1 and 4 show a left roll, frame 2 shows a right roll, while frames 3 and 5 show the airplane in level flight. The amount of roll cannot be derived as easily as the other attitude variables, because this information is derived from the asymmetry of the picture. This will be explained in more detail in the next section.

Figure 34 shows pictures of the screen for the various views, illustrating the sketches in Figs. 32 and 33.

5.d. Evaluation and Comments.

The design principle for the perspective display is twofold :

1) it is intended to give the pilot the information in one coherent map and not as a superposition,
2) to give a minimum set of lines to yield all the necessary information,

but in such a manner that no confusion will occur and that the display is satisfactory to give a quantitative information for the prescribed task.

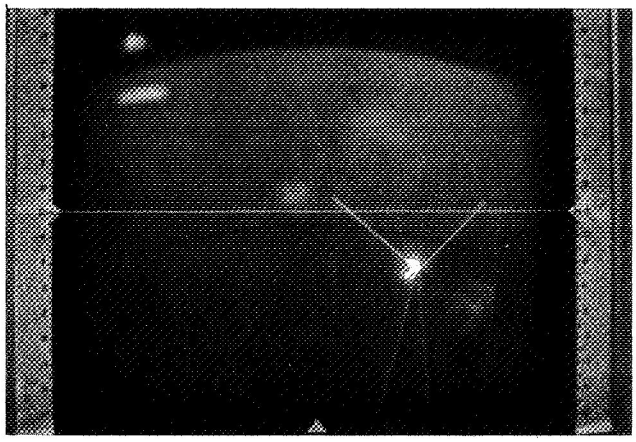


Fig. 34a. The display as seen at the start of the flight. The aircraft's position is 800 ft to the left of the localizer.

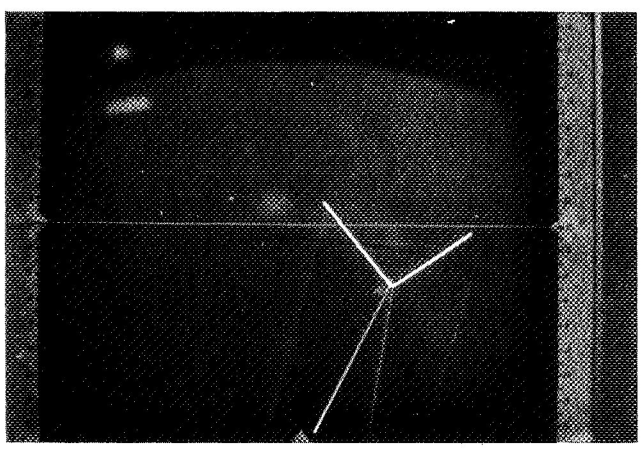


Fig. 34b. The display as seen in the same position as in Fig. 34a. This time, the aircraft has a left roll, which will bring it further away from the localizer.

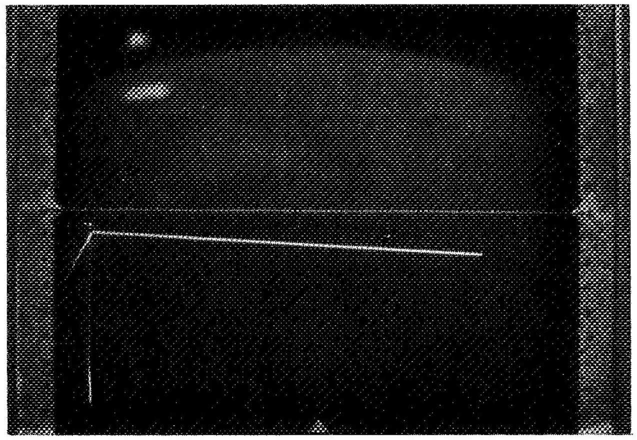


Fig. 34c. The display as seen 60,000 ft from the runway. The aircraft is on the glideslope, to the right of the localizer. It has no roll, and it is headed far to the right of the runway.

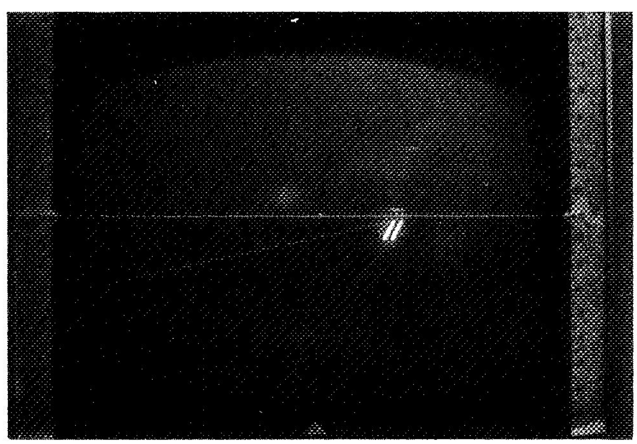


Fig. 34d. The display as seen 50,000 ft from the runway. The aircraft is above the glideslope, a little to the right of the localizer. It has no roll, and it is headed to the left of the runway.

The present proposed picture is limited by the available equipment, and this section is intended to give a survey of the comments and solutions to specific problems.

1. If one reads the picture statically, it is sometimes difficult to read the roll information. With the present configuration it is derived from the asymmetry of the picture, or from the tilted position of the vertical poles. However, the addition of the horizon line will help overcome this difficulty , and this addition is still in agreement with the display design principle.

2. An exact read-out of the variables can be desirable. A graphics terminal can solve this problem. The numbers should change only at regular intervals such that the pilot has time to read the numbers.

3. For unusual positions, such as position 2 in Figure 29, it will be helpful to give the glideslope lines a different color than the extended ground lines.

4. For other tasks than landing, a waveoff maneuver or a curved approach for example, a different display program is advisable, which the pilot would be able to select with a mode switch. Similar skeleton-type pictures could be worked out, depending upon the task.

5. Indications of obstacles could be included. The obstacle should be linked to the rest of the picture with groundlines perpendicular to the localizer.

6. Indication of a desired forward speed or the deviation from it, could be indicated with poles moving away or towards

the center of the screen depending upon the case, flying too fast or too slow.

5.e. Pilot opinion.

It is a recognized fact that pilot opinion is a significant factor in determining important design decisions on new aircraft (34). Flying qualities cannot be represented by a measurable number in several instances, and must therefore be judged by pilot opinion. Reference 34 describes various approaches and aspects of this method, and table 3 gives the pilot opinion rating system.

No strong emphasis has been put on this rating during all phases of the experiment, except in the study of the three-dimensional motion. The opinion of the experienced pilots has been asked for, and their comments are listed below :

1. It is desired to have a sensitive reading of sink rate as well as altitude near touchdown.
2. A horizon line is desirable for a better reading of the roll attitude.
3. It is desirable to have a localizer centerline to eliminate small lateral oscillations. This was found to be true, optically speaking.
4. Heading should be indicated on the horizon line, using marks every 5 degrees or so.

In terms of the same rating system, the experiments with three degrees of freedom yielded a numerical rating 6 for the conventional dials, and a rating of 2-3 for the perspective display.

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accompl	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

*Failure of a stability augmenter

TABLE 3. Cooper Pilot Opinion Rating System.

5.f. Comparison of the perspective display with others.

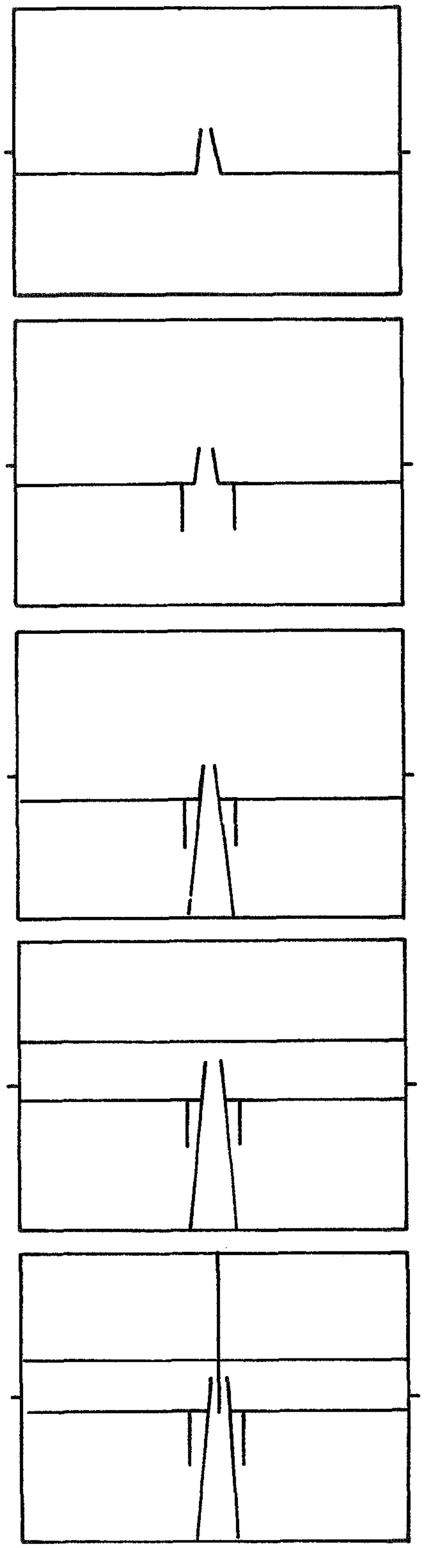
Various changes have been made to the perspective display for landing during the course of the experiment, by incorporating the suggestions of the pilots. The rearrangement in the line configuration was done to achieve a better level of performance for a specific flight variable.

Fig. 35 shows the various display formats. The significant factors in selecting the different lines are :

- runway cue : for simulating VFR conditions
- glideslope lines : for tracking the glideslope
- distance poles : to indicate a desirable change in the flight mode
- groundlines : to show the proximity of the terrain in order to obtain smoother touchdowns
- horizon line : to indicate better the amount of roll
- localizer line : for tracking the localizer

Besides the status information on position, the attitude is indicated relative to the runway and the landing spot, rather than as an absolute quantity.

The display did not include numbers on the screen, and it has some similarity with displays 3 and 4 in Fig. 36a. The other display types in this figure are basically integrated displays (they bring on one screen the information otherwise displayed on several dials) and they all display the information as follows :



VISUAL CUE OF THE RUNWAY

GLIDESLOPE LINES

DISTANCE POLES

GROUNDLINES

HORIZON LINE

LOCALIZER CENTERLINE

Fig. 35. The various display formats that have been examined.

- pitch, as a vertical motion of the horizon line
- roll, by rotation of the horizon line
- heading, by marks on the horizon line
- command heading and pitch, with a director symbol
- status altitude, by means of a scale or moving tape
- rate of descent, by means of a scale or a marker
- airspeed, on a scale
- deviation from the glideslope, using a moving symbol
- deviation from the glidepath, using a moving symbol

All of the displays are of the inside-out type, giving status information and where the appropriate response is fly-to. None of the displays provides inner loop closure, and they only alleviate the pilot workload by reducing the scanning time. They also reduce the possibility of misreading the status information.

A display which has some things in common with this perspective display is the SAAB Pole Track display (Ref. 80). It is also a contact analog display of the skeleton type. It has the landing path displayed and the horizon line, as well as the distance poles. However it does not have the glideslope or localizer lines, but it has instead quite a number of poles. The pilot has to track the top of the poles (hence the name : Pole Track) to stay on the glideslope. The author was fortunate to have seen a movie of the Pole Track display. Some of the comments of our display scheme-one are applicable to the Pole Track display.

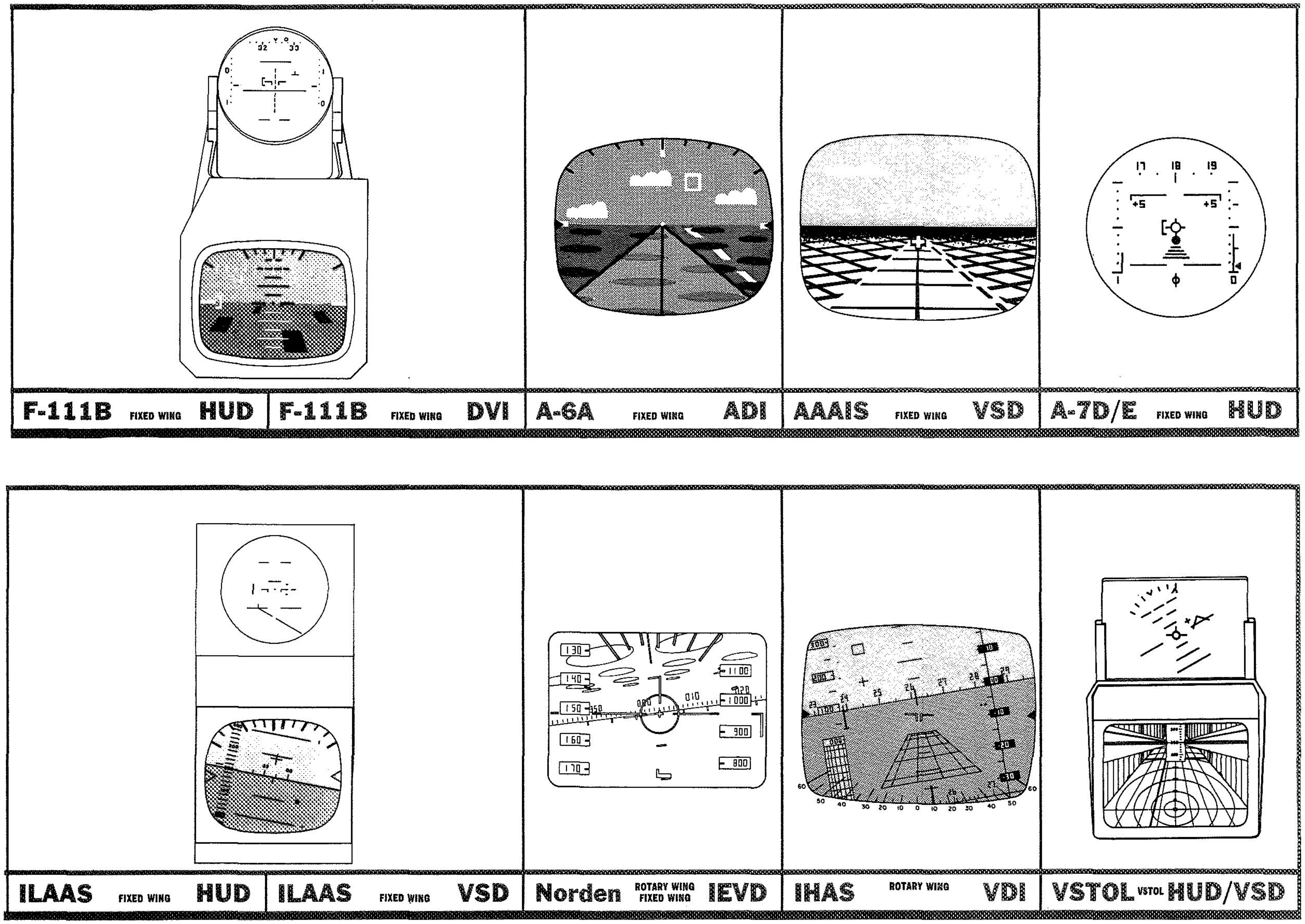


Fig. 36a. Examples of Vertical Situation Displays (Ref. 80).

	F-111B HUD	F-111B DVI	A-6A ADI	AAAIS VSD	A-7D/E HUD	ILAAS HUD	ILAAS VSD	Norden IEVD	IHAS VDI	VSTOL HUD/VSD
PITCH ANGLE	√	√	√	√	√	√	√	√	√	√
PITCH TRIM	√	√	√	√			√			
ANGLE OF ATTACK	√	√	√		√	√				
ROLL ANGLE	√	√	√	√	√	√	√	√	√	√
HEADING	√	√			√		√	√	√	
STEERING	√	√	√	√	√	√	√	√	√	√
TURN RATE								√		
VERTICAL ORIENTATION	√	√	√	√	√		√	√	√	√
ALTITUDE	√			√	√		√	√	√	√
VERTICAL VELOCITY	√				√			√	√	
AIRSPEED				√	√			√	√	
VELOCITY VECTOR			√	√	√	√	√		√	√
PULL-UP			√							
GLIDESLOPE	√	√	√	√	√			√	√	√
GLIDEPATH	√	√	√	√	√	√		√	√	√
WAVEOFF	√	√			√					
PATHWAY										
SIDESLIP								√		
RUNWAY HEADING ERROR										
RUNWAY DISTANCE										
HOVER POSITION								√		√
RANGE TO GO										√
GROUNDSPEED									√	
HOVER GROUNDSPEED								√	√	√
LATERAL GROUND VELOCITY								√	√	√

Fig. 36b. Information for landing, given by the displays in Fig. 36a. (Ref. 80)

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.a. Results and Conclusions

It is often argued that a human operator is limited in his ability to control a system. An experiment has been set up to check the validity of this argument in the landing of a VTOL aircraft. A variety of pilot-subjects has been examined when controlling a VTOL aircraft of the tilt-engine type. The simulated aircraft did not possess any stability augmentation. The pilots performed a task, consisting of tracking the glideslope from cruise to hover, and of landing the simulated aircraft under category III conditions. The imposed glideslope varied from the range of the conventional one (3°) to the steep glideslope case of 17.5°. Severe wind disturbances were applied to test the pilot's tracking ability. To improve the pilot's performance, a perspective glideslope indicating system was provided.

6.a.1. Piloting Techniques

It was observed that the pilot's approach in controlling the aircraft depends upon his familiarization with the aircraft dynamics, from their first experience with the simulator. Experienced pilots control the aircraft exhibiting a second order lead while tracking the glideslope.

Inexperienced pilots, on the other hand, control the aircraft as a pure gain system at the start of their training. Gradually, after learning and training, they change to a first order system, and then to a second order system. The speed with which they learn depends upon their ability to understand the situation while flying the simulated aircraft.

When applying the random disturbance, the experienced pilots go through a similar training period but it is of a shorter time. Inexperienced pilots hardly reach the same level of performance, and fatigue is observed at quite an early stage.

Occasionally, during the experiment, some instruments go off scale. This results in a drastic change of the human operator control. He merely acts as a pure time delay and the delay depends upon the degree of ignorance.

Finally, it has been observed that different techniques were used depending on the glideslope. For the steep glideslopes, the experienced pilot behaved as a time varying controller between first and second order. Medium experienced pilots tend to control this way, too.

6.a.2. Tracking Ability

The ability to track the glideslope is a direct measure of the level of performance the pilot has reached. The error score derived by means of an absolute weighted error sum of the deviation from the glideslope, shows the progress the pilot makes as time goes on. It turns out that this score too is highly correlated with the pilot's performance at touchdown.

The use of the glideslope indicating system improves the error score by an order of magnitude, while the learning time for all three classes of pilots has become negligible. In fact, when a novice is told what the tracking task consists of, in seconds he has learned how much lead and what gains to use. When the display is blanked manually to cause some deviation to show up, the response of the pilot is always one with dead beat response, as soon as the display is turned on again.

6.a.3. Consistency in Touchdowns

Without the contact analog displays, the standard deviation for the touchdown range as well as for the touchdown velocity is quite high. The best touchdown velocities were obtained where the pilot executed a flare preceeded by a duck-under maneuver. This way of landing, however, brought along a substantial error in touchdown range.

With the perspective glideslope indicating system, the standard deviation for the touchdown range as well as for the touchdown velocity is significantly less. Moreover, the mean value for both of these quantities is much closer to the desired values (i.e. 90,000 ft and less than 6 ft/sec, respectively). It is interesting to note that with the display a coordinated change of the flight variables using various controls has become an easy task, unlike the instrument approach where the pilot uses a stepped-up technique. In the latter method, the pilot changes only one variable at a time.

6.b. Applications for the Display

The results have shown that the display allows coordinated maneuvers much better than with the conventional instruments, which are more efficient than any stepped-up approach control. For these reasons, it is very promising in the following applications:

1. Steep Approach Paths

The difficulty in tracking the glideslope goes up as the slope increases. Present approaches are made with a 3 degree glideslope. Using the display, it will be possible to have simultaneous approaches at different angles, where the paths can be followed in a very narrow band. If the air traffic would not be allowed to have simultaneous approaches in a single plane and at different angles, but rather in different planes and small distances apart, the display will do again. Further, the steep approach has two interesting applications: first, the noise problem can be solved greatly by allowing aircraft to "drop out of the sky," second, the supersonic transport can be arranged to operate more efficiently by staying up much longer in the air at maximum speed, while the steep descent path would be used to decelerate the aircraft.

2. Carrier Landing

Due to its variability and adaptability for the missions or the configuration, the perspective display can be worked out for the aircraft carrier landing. Steep approaches can be combined with accurate landings and smooth touchdowns, even in zero-zero visibility.

3. Helicopter Approaches

Although not worked out as a specific example, helicopter landings on a roof top are quite feasible. Again in zero-zero visibility, a different line pattern would be drawn to make hover easier. Rather than having a Horizontal Situation Display (HSD), the screen could be placed at an angle to have partial advantage of a Vertical Situation Display (VSD).

4. Visual Simulation Training Aid

In real flight situations, the pilot derives a great deal of information by looking out the window. Furthermore, all landings are presently terminated VFR even though the approach to the decision height may be IFR. For training purposes, fixed-base simulators are better than theoretical lessons. Moving base simulators are still better. However, some visual contact will help further to understand the flight situation, where instruments or motion may upset the student-pilot when he becomes disoriented. Indeed, the possibility of being able to turn on or to turn off the display showed its help during recovery from unusual situations, which otherwise normally resulted in "crashes."

6.c. Recommendations for Further Study

Immeasurable time has been spent in setting up the experimental apparatus, in writing innumerable programs to do the job, and in testing out the overall system. The programming has been quite general so that with a minimum of modifications even a whole new experiment could be worked out.

1. From the display point of view, a number of applications are feasible. First, the display can be used to study the lateral response of the pilot controlling the VTOL aircraft. The program need only have more realistic lateral dynamics with some of the longitudinal dynamics. It would be quite interesting to know if the control of the lateral dynamics is also performed as a time varying model for the steep glideslope approach. Secondly, the line configuration of the display can be modified to resemble the roof top of a building with an appropriate "roadway in the sky." Techniques to make hidden lines invisible have been successfully applied (Ref. 97). Thirdly, a display could be

designed to represent a roadway in the sky for take-off applications, for example, or fulfill the role of an electronic attitude indicator for supersonic aircraft. This study would indicate if it is possible to fly "the optimum path" under severe circumstances. For the SST aircraft, for example, it is known that keeping altitude is not an easy task. Finally, it is also possible with this general display concept to duplicate some of the vertical situation displays under development (Ref. 80). It would then be possible to compare performance obtained using different displays.

2. From the control point of view, it would be rewarding to test the performance of the pilot using the perspective glideslope indicating system and to compare it with an automatic control system (preferably designed using optimal control theory). Both systems would be examined using the same aircraft dynamics while performing the same task.

3. From a practical point of view, it would be interesting to study some other aspects using exactly the same set-up, namely economy, density and noise. It has been shown that economy depends largely on the flight path followed (82). It remains to be investigated if the improved display concept will make these paths feasible. For the noise problem, it would be interesting to find out

how much of an improvement can be obtained in coming down following a steep approach with power off using well known formulas for noise propogation. Finally, from the point of view of air traffic density, it would be interesting to find out how much the traffic flow could be increased using multiple approach paths with shorter descent periods and with smaller spacing. Of course, safety would have to be looked at by considering a given level of confidence.

6.d. Synthesis.

The perspective display has been investigated as a means of instrumentation for V/STOL aircraft in the landing phase. The examination is a design method for comparing displays.

The research for this thesis has explored fully the ideas and concepts of the perspective display. The important contributions can be synthesized as follows :

1. The present perspective display is a contact analog display, and the attitude and position information is presented as a realistic and coherent map, rather than in an integrated fashion or in a way which is a combination of both. No moving parts move in opposite direction and hence reduces confusion.
2. The display is of the skeleton type, rather than of a pictorial nature. It uses a minimal set of lines to give the pilot the desired information necessary to perform the landing task. The configuration yields a quantitative read-out for excellent performance.

3. The important feature of the display is that the attitude and the position information are visually linked in the picture. It allows the pilot to control the aircraft in an adaptive manner and allows a dead beat response while nulling errors in deviation from the glideslope and the glidepath.
4. The display is very suitable for coordinated control changes unlike stepped-up approaches. It gives the pilot a better and faster interpretation of the flight condition and hence allows a continuous control rather than a sampling-and-hold strategy based on estimation.
5. The display evaluation has been done in a full mode of operation. The pilot has a specific landing task and his overall performance is examined : quality, strategy and learning.
6. Special programming techniques have been incorporated to help realize the study with moderate equipment. More expensive graphics terminals or larger computing facilities would facilitate this task. On-board equipment however will require a limited computing system for practical purposes.

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Noël A.J. Van Houtte was born in Grammene, Belgium in 1940. He got his high school education at the Sint-Hendrikscollege, Deinze and was awarded the Golden Medal "Primus Perpetuus" in 1958. He entered the State University of Gent in 1959 with a first place of more than 200 participants at the entrance examination for the School of Engineering. He received the degree of kandidaat burgerlijk ingenieur summa cum laude in 1961, and the degree of burgerlijk werktuigkundig elektrotechnisch ingenieur magna cum laude in 1964.

He was working with the SABENA Belgian World Airlines in the summer of 1964. He was instructor in the Laboratory of Machines and Construction of Machines of the State University of Gent in 1964-65.

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